Report No. UT- 4.12

REGIONAL FLOOD FREQUENCY ANALYSIS FOR SELECTED BASINS IN UTAH

Part II: Weber River Basin

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16. Abstract

The main objective of the study was to improve the accuracy of estimates of 5-, 10-, 25-, 50- and 100-yr peak discharge values for ungaged, unregulated watersheds in the Weber River basin. Detailed flood-frequency analysis was done for streamflow gaging stations in and around this basin. Flood frequency prediction equations for selected recurrence intervals were developed using a regression model with selected watershed and meteorological characteristics as explanatory variables. The work completed in Part I and Part II also contributed to the development of a map for the entire State of Utah depicting site-specific skew coefficients for use in the flood frequency analysis.

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1. INTRODUCTION

1.1 Purpose

Accurate estimates of peak discharge values of different frequencies are needed for the hydraulic design of instream structures and for floodplain management. The structure size is determined largely by the hydraulic properties necessary to convey peak streamflow. While under-designing a structure could cause disruption of service and costly maintenance, over-designing will result in excessive construction costs and in some cases additional environmental impacts.

When a systematic flood record of sufficient length is available at the site where a peak discharge estimate is needed for design work, and when the floods are not affected by regulations or diversions, flood frequency analysis can be used to characterize flood potential at the site of the design work. Procedures described in Bulletin 17B “Guidelines for Determining Flood Flow Frequency” (Hydrology Subcommittee of the Interagency Advisory Committee on Water Data, 1982) are commonly used to compute flood flow frequency estimates at unregulated, gaged sites.

For locations at which flood records are not available, traditional approaches use “single-return-period” prediction equations that relate a peak discharge of a specific return period to one or more watershed and meteorological characteristics. These equations are usually of the log-log multivariate regression form. They are developed for a region that is identified as homogeneous based on underlying hydrological/meteorological properties.

1.2 Weber River Basin Description

This report focuses on the development of regional regression equations for the Weber River Basin watershed. This watershed is located in northern Utah, with a very small portion extending into Wyoming (see Figure 1). The watershed is composed of a flat, fertile valley east of the Great Salt Lake. Rising abruptly from the valley floor are the Wasatch Mountains, which extend in a north-south direction and divide the interior of the watershed from the flat valley. The southeast corner of the basin is located high in the Uinta Mountains. The topographic relief across the watershed is more than 7,500 feet, varying from an elevation of 11,708 ft (Reids Peak) in the Uinta Mountain range to approximately 4,200 ft at the elevation of the Great Salt Lake. The watershed contains approximately 2,060 square miles.

Due to the substantial differences in elevation within the watershed the precipitation pattern varies greatly. Average annual precipitation ranges from 12 to 30 inches. Snow accumulation and melt is a very significant feature in terms of the annual hydrologic cycle for this watershed. The annual water yield for this basin has been estimated to be 980,000 acre-feet. The principle uses of water in the Weber Basin are for agricultural irrigation, and for municipal and industrial uses. The overall growth rate for the basin is projected to be 2.3%. More detailed information on watershed physiography and drainage can be found on the Utah Department of Environmental Quality web page (http://waterquality.utah.gov/watersheds/state.htm).

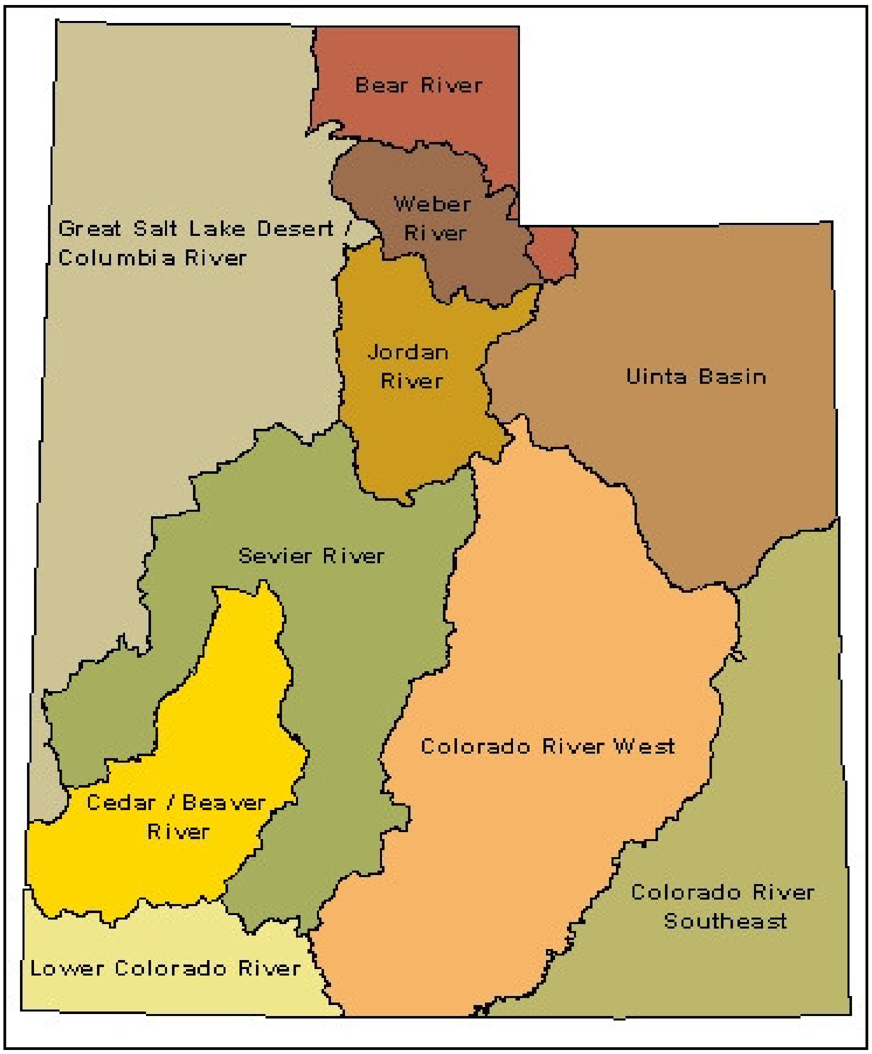

Figure 1. Location of the Weber River basin (http://waterquality.utah.gov/watersheds/state.htm).

2. DATA ANALYSIS

2.1 Data Source

The data used in this report were obtained solely from the U.S. Geological Survey (USGS) database. Attempts to obtain annual instantaneous peak flow data from other sources provided no additional information. The Utah Park and Recreation, Utah National Park Service, Utah Geological Survey, State Trust Lands, and Natural Resources Conservation Service were all contacted and it was discovered that none of them collect instantaneous annual peak streamflow data in the state of Utah. The U.S. Forest Service and the Colorado River Basin Forecast Center of the National Weather Service provided some data, but they were insufficient to be included in this analysis.

The USGS database contains systematic records for 46 surface-water gaging stations located in the Weber Basin watershed. The number of stations that the USGS maintains varies annually. Only 16 of the 46 sites are currently operational; their locations are shown in Figure 2.

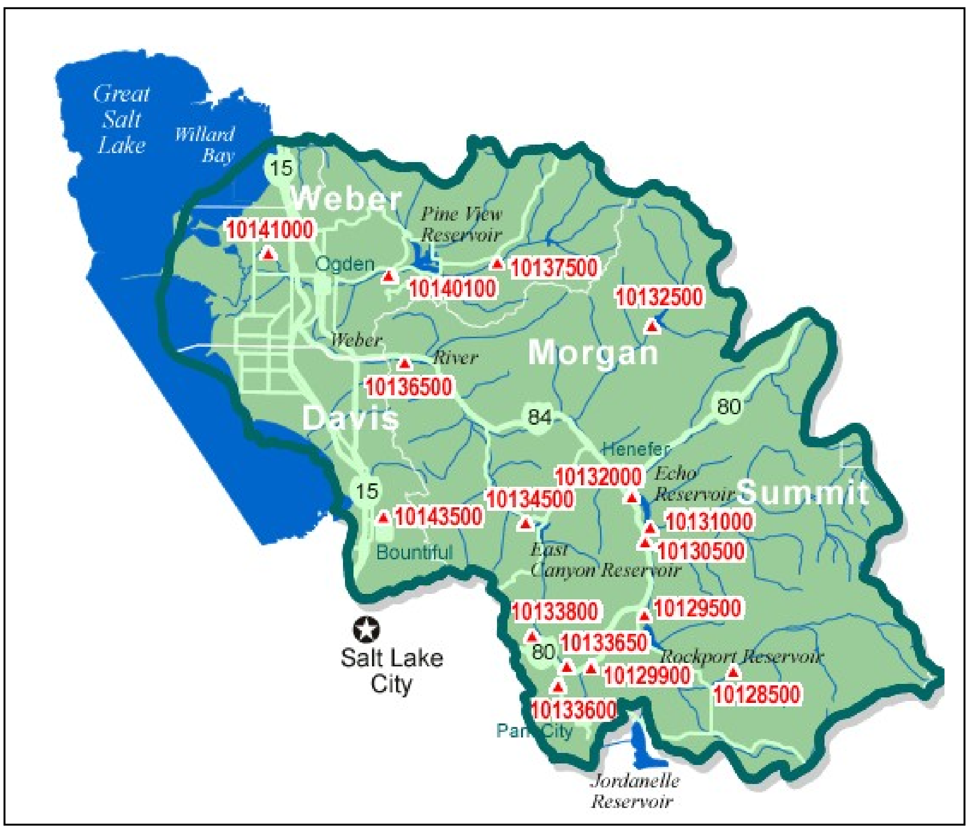

Figure 2. Weber River basin and current USGS gage sites. (http://ut.water.usgs.gov/Basins/WeberRiverBasin/index.html)

2.2 Selection of Study Area

The study area was located between 40.25° and 41.75° North Latitude and 110.75° and 112° West Longitude (Figure 3). There are 135 USGS streamgages in the region (see Figure 3 for site locations; see also Appendix 1 for a list of all sites in the study area).

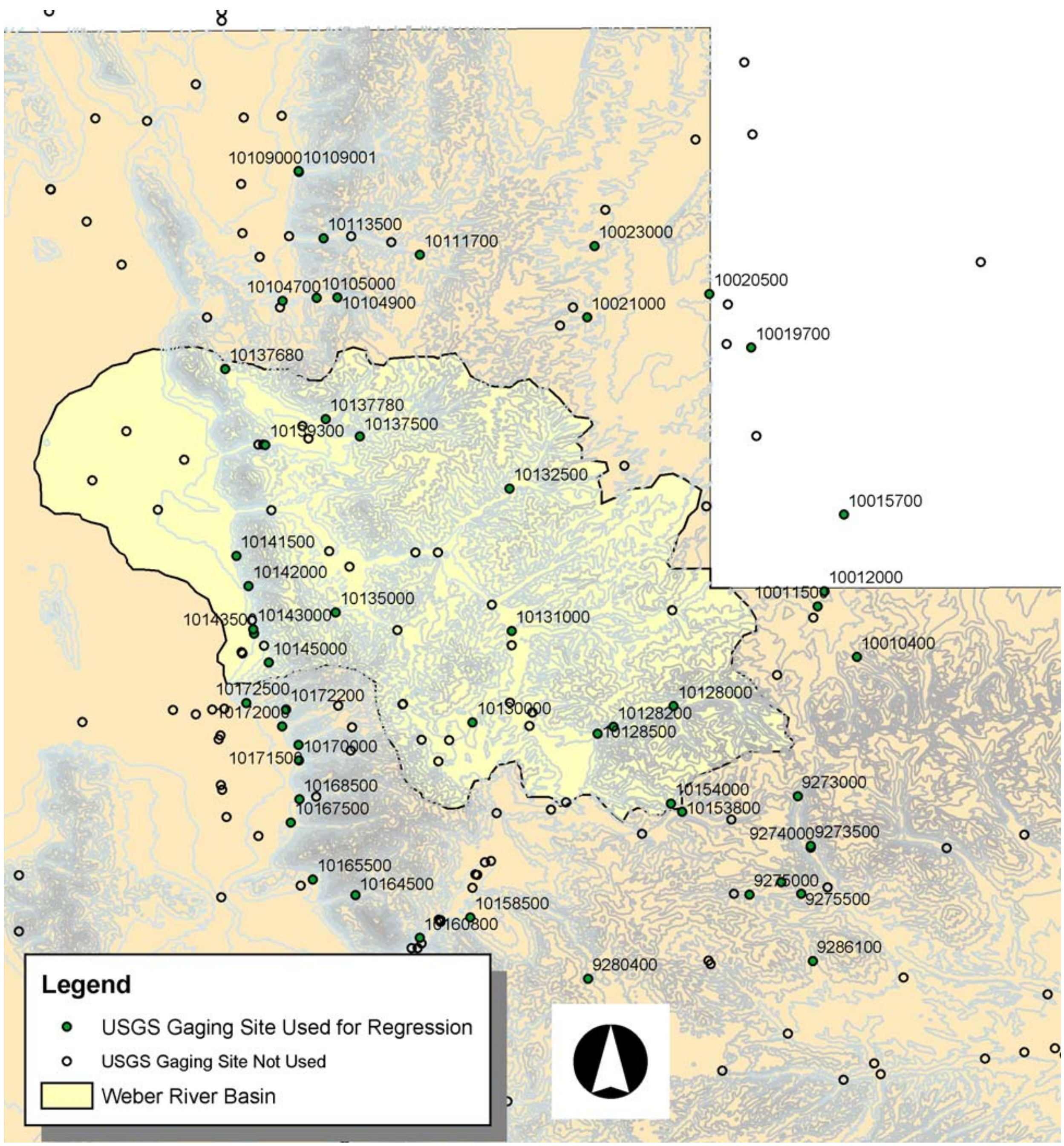

Figure 3. Study area with USGS streamgages. Green circles indicate sites used in frequency analysis.

2.3 Data Assumptions

Certain data assumptions must be met in order to apply the frequency analysis approach outlined in Bulletin 17B. Our first criterion for using a site in the flood frequency analysis was that it has at least 10 years of systematic record, after low outliers are removed. This meant the elimination of 35 sites (designated in Appendix 1 as *Insufficient Data*).

Another assumption built into Bulletin 17B is that the site flows are not affected by diversion or regulation. Accordingly, an additional 38 sites were eliminated from the analysis (designated in Appendix 1 as *Diversion/Regulation*).

Upon further consideration, additional sites were removed from the data set. There were seven sites that were removed because they are not in natural streams (designated in Appendix 1 as *Urban Site*). Site 10133700 was removed because it did not contain continuous data, and data were not reliable (designated in Appendix 1 as *Non-Continuous Record*). Also, sites 10142500 and 10144000 have been removed because they contained estimated annual peak flows (designated in Appendix 1 as *Estimated Flow).* Sites 10109000 (Logan River above State Dam near Logan, UT) and 1018401 (Logan, Hyde Park and Smithfield Canal at head near Logan, UT) were removed from the data set, as well. Site 10109001 combines discharges from those two sites and measures the natural flow for the Logan River. Statistical analyses were performed on the remaining 50 sites listed in Table 1 (for site locations see Figure 3).

2.4 Low and High Outliers

According to Bulletin 17B, data outliers are “data points which significantly depart from the trend of the remaining data.” All data sets were checked for low outliers in accordance with ~~to~~ the Bulletin 17B approach for detecting and treating outliers. There were 17 sites identified in the study area that contained one or more low outliers (see Table 2). All low outliers were censored and the conditional probability adjustments were made to obtain the final frequency relationships.

Data sets were also checked for high outliers. Seven stations, each with a single high outlier, were detected in the final study area (see Table 3). Unlike the low outliers, and in accordance with Bulletin 17B recommendations, these high outliers were retained as part of the data set.

Table 1. USGS streamgages used in frequency analysis.

Site number	Name	Years of record	Latitude (degrees)	Longitude (degrees)	Elevation (ft)
09273000	Duchesne R At Provo R Trail Nr Hanna, UT	22	40.625	110.890	8136
09273500	Hades Creek Near Hanna, UT	19	40.536	110.867	7460
09274000	Duchesne River (N.Fork) Near Hanna, UT	20	40.533	110.867	7380
09275000	W F Duchesne River Bl Dry Hollow Nr Hanna, UT	26	40.449	110.976	7656
09275500	West Fork Duchesne River Near Hanna, UT	50	40.450	110.884	7218
09276000	Wolf Creek Above Rhoades Canyon Near Hanna, UT	39	40.471	110.919	7740
09280400	Hobble Creek At Daniels Summit Near Wallsburg, UT	21	40.298	111.265	8200
09286100	Red Creek Above Reservoir, Near Fruitland, UT	12	40.330	110.863	7320
10010400	East Fk Bear River Nr Evanston, WY	13	40.874	110.784	8760
10011500	Bear River Near Utah-Wyoming State Line	59	40.965	110.854	7965
10012000	Mill Creek At Utah-Wyoming State Line	19	40.992	110.842	7860
10015700	Sulphur Cr.Ab.Res.Bl.La Chapelle Cr.Nr Evanston,WY	40	41.129	110.807	7180
10019700	Whitney Canyon Creek Near Evanston, WY	17	41.428	110.973	6710
10020500	Bear River Near Woodruff, UT	20	41.524	111.048	6360
10021000	Woodruff Creek Near Woodruff, UT	32	41.482	111.267	6600
10023000	Big Creek Near Randolph, UT	41	41.610	111.254	6410
10104700	Little Bear R Bl Davenport C Nr Avon, UT	32	41.512	111.812	5020
10104900	East Fk Lt Bear Riv Ab Resv Nr Avon, UT	23	41.518	111.714	5390
10105000	East Fork Little Bear R Nr Avon, UT	13	41.517	111.751	5250
10109001	Com F Logan R Ab St D And Lo Hp And Sm C N Lo, UT	83	41.744	111.784	4680
10111700	Blacksmith F B Mill C N Hyrum, UT	11	41.594	111.567	5545
10113500	Blacksmith Fork Ab U.P.&L. Co,S Dam Nr Hyrum, UT	82	41.624	111.739	5021
10128000	Smith And Morehouse Creek Near Oakley, UT	11	40.786	111.112	
10128200	South Fork Weber River Near Oakley, UT	10	40.749	111.220	6800
10128500	Weber River Near Oakley, UT	97	40.737	111.248	6640
10130000	Silver Creek Near Wanship, UT	14	40.757	111.472	6360
10131000	Chalk Creek At Coalville, UT	76	40.921	111.402	5561
10132500	Lost Creek Near Croyden, UT	29	41.176	111.406	5820
10135000	Hardscrabble Creek Near Porterville, UT	29	40.954	111.717	5500
10137500	South Fork Ogden River Near Huntsville, UT	81	41.269	111.674	5190
10137680	North Fork Ogden River Near Eden, UT	11	41.390	111.915	5750
10137780	Middle Fk Ogden River Ab Div Nr Huntsville, UT	11	41.300	111.735	5400
10139300	Wheeler Creek Near Huntsville, UT	37	41.254	111.843	4800
10141500	Holmes Creek Near Kaysville, UT	18	41.055	111.895	5095
10142000	Farmington Cr Abv Div Nr Farmington, UT	34	41.001	111.873	5100
10143000	Parrish C Ab Diversions Nr Centerville, UT	20	40.924	111.865	4600
10143500	Centerville Creek Abv. Div Near Centerville, UT	31	40.916	111.863	4680
10145000	Mill C At Mueller Park, Nr Bountiful, UT	20	40.864	111.837	5240
10153800	North Fork Provo River Near Kamas, UT	33	40.597	111.097	7480
10154000	Shingle Creek Near Kamas, UT	10	40.612	111.117	7700
10158500	Round Valley Creek Near Wallsburg, UT	12	40.408	111.476	5480
10160800	No Fk Provo Riv At Wildwood, UT	10	40.371	111.567	5420
10164500	American Fk Ab Upper Powerplant Nr American Fk, UT	70	40.448	111.682	5950
10165500	Dry Creek Near Alpine, UT	19	40.476	111.758	5320
10167500	Little Cottonwood Creek Nr Salt Lake City, UT	51	40.578	111.798	5080
10168500	Big Cottonwood Cr Nr Salt Lake City, UT	60	40.619	111.782	4990
10170000	Mill Creek Near Salt Lake City, UT	63	40.689	111.783	5050
10172000	Emigration Creek Near Salt Lake City, UT	57	40.750	111.813	4870
10172200	Red Butte Creek At Fort Douglas, Near SLC, UT	38	40.780	111.806	5400
10172500	City Creek Near Salt Lake City, UT	72	40.792	111.877	4540

Table 2. USGS gaging sites containing low outliers in the study area.

Site Number	Number of Low Outliers
09275000	1
09275500	4
09276000	2
09280400	2
10104900	2
10109001	1
10130000	1
10135000	3
10137500	3
10137780	1
10153800	2
10158500	1
10164500	1
10168500	1
10170000	2
10172000	2
10172500	1

Table 3. USGS gaging sites containing high outliers in the study area.

Site Number	Number of High Outliers
09274000	1
09276000	1
10015700	1
10143500	1
10164500	1
10165500	1
10172500	1

2.5 Historic Floods

At some gaging stations, in addition to the systematic record, historic flood information is available. Four sites in our study area contain this type of information (sites 10141500, 1014300, 10143500 and 1014500). The Bulletin 17B approach was again used to adjust the frequency curves for these gaging stations.

2.6 Urbanization Trend

A statistical flood frequency analysis is based on the assumption of homogeneous annual flood records. Urbanization is a primary cause of non-homogeneity of flood records. Based on the information obtained from the State of Utah, Department of Environmental Quality web site (http://waterquality.utah.gov/watersheds/state.htm) that the overall basin has been sparsely populated and that the growth rate for the basin is projected to be 2.3%, we made a hypothesis that the impact of urbanization on the magnitudes of the measured flood peaks has been relatively low.

This hypothesis was tested in two ways. First, a time series plot with a linear regression line was made for each site in the study area that had over thirty years of usable data (see Appendix 2). Approximately half of the sites had positively sloping regression lines and half had negatively sloping regression lines, and none of them showed significant trends. We also examined the effect of urbanization on the annual peak time series using one-sided non-parametric Spearman-Conley test at a 5% significance level (McCueen, 1998). An assumption was made that if annual peak flows are not serially correlated based on this statistical test, then urbanization does not have an effect on peak flows. The test did not indicate a significant positive trend in time for annual peaks at any gaging station in the study area. Because of that, changes in the watershed due to urbanization were judged to have been gradual in the last 30 years, and their cumulative effect on runoff insignificant.

2.7 Seasonal Effects

Flood populations can result from different hydrometorological conditions. Annual peaks can result from different rainstorm types (e.g., cyclonic storms, summer thunderstorms), or snowmelt, rainfall on snow events, etc. In those instances it may be necessary to segregate flow record by cause and to carry out separate frequency analysis for each data set, and combine them together using composite relations (Kite, 1977).

Flood records were carefully examined in lieu of separation. Separation by calendar periods is usually assumed to represent separation by cause (although that is not always the case). The flood records were broken out into percentage of peak flows occurring in a given month. As can be seen from Table 4, a vast majority of events occurs between April and June, independent of station location or the mean basin elevation. Therefore it was assumed that peak flows resulted from similar hydrometeorological conditions, and that no separation of flood records is needed.

Table 4. Seasonal analysis. Percent of peak flows occurring in given month.

Site	Altitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
09273000	8136	0	0	0	0	43	57	0	0	0	0	0	0
09273500	7460	0	0	0	0	16	84	0	0	0	0	0	0
09274000	7380	0	0	0	0	30	70	0	0	0	0	0	0
09275000	7656	0	0	0	0	56	44	0	0	0	0	0	0
09275500	7218	0	0	0	0	70	28	0	0	0	2	0	0
09276000	7740	0	0	0	3	50	44	3	0	0	0	0	0
09280400	8200	0	0	0	0	68	32	0	0	0	0	0	0
09286100	7320	0	0	17	17	50	17	0	0	0	0	0	0
10010400	8760	0	0	0	0	23	69	8	0	0	0	0	0
10011500	7965	0	0	0	0	39	61	0	0	0	0	0	0
10012000	7860	0	0	0	5	68	26	0	0	0	0	0	0
10015700	7180	0	0	13	55	24	8	0	0	0	0	0	0
10019700	6710	0	0	35	47	0	6	0	6	6	0	0	0
10020500	6360	0	0	5	20	45	30	0	0	0	0	0	0
10021000	6600	0	0	0	4	78	11	4	4	0	0	0	0
10023000	6410	0	0	30	5	35	3	5	10	0	8	5	0
10104700	5020	9	9	13	31	25	9	0	0	0	0	0	3
10104900	5390	0	0	5	52	43	0	0	0	0	0	0	0
10105000	5250	0	0	0	77	23	0	0	0	0	0	0	0
10109001	4680	0	1	1	1	61	35	0	0	0	0	0	0
10111700	5545	9	0	27	27	18	9	0	0	0	9	0	0
10113500	5021	0	4	5	39	44	2	1	0	0	4	0	1
10128000		0	0	0	0	27	73	0	0	0	0	0	0
10128200	6800	0	0	0	0	30	70	0	0	0	0	0	0
10128500	6640	0	0	0	0	39	60	1	0	0	0	0	0
10130000	6360	0	0	38	46	15	0	0	0	0	0	0	0
10131000	5561	0	3	4	12	68	9	0	4	0	0	0	0
10132500	5820	0	0	0	32	68	0	0	0	0	0	0	0
10135000	5500	0	0	0	12	65	12	4	4	0	0	0	4
10137500	5190	0	0	0	33	64	0	0	0	0	0	0	2
10137680	5750	9	0	0	27	36	18	9	0	0	0	0	0
10137780	5400	0	0	0	0	100	0	0	0	0	0	0	0
10139300	4800	6	6	22	42	17	6	0	0	0	0	0	3
10141500	5095	0	0	0	11	67	17	6	0	0	0	0	0
10142000	5100	0	0	3	9	79	9	0	0	0	0	0	0
10143000	4600	0	0	0	5	80	15	0	0	0	0	0	0
10143500	4680	0	0	0	13	77	10	0	0	0	0	0	0
10145000	5240	0	0	0	15	70	15	0	0	0	0	0	0
10153800	7480	0	0	0	0	61	35	3	0	0	0	0	0
10154000	7700	0	0	0	0	50	50	0	0	0	0	0	0
10158500	5480	0	0	18	36	36	0	0	0	0	0	0	9
10160800	5420	0	0	0	0	40	60	0	0	0	0	0	0
10164500	5950	0	0	0	3	55	39	1	1	0	0	0	0
10165500	5320	0	0	0	0	33	39	11	17	0	0	0	0
10167500	5080	0	0	0	0	45	55	0	0	0	0	0	0
10168500	4990	0	0	0	0	58	42	0	0	0	0	0	0
10170000	5050	0	0	0	0	66	34	0	0	0	0	0	0
10172000	4870	0	0	9	55	31	5	0	0	0	0	0	0
10172200	5400	0	3	8	39	50	0	0	0	0	0	0	0
10172500	4540	0	0	0	3	80	17	0	0	0	0	0	0

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3. REGIONAL SKEW MAP

Bulletin 17B recommends using the Log-Pearson Type III (LP3) probability distribution and the method of moments to define flood-frequency relations. The accuracy of all statistical moments, and particularly skew, is a function of sample size. A sample skew coefficient is very sensitive to extreme events, therefore it is recommended in Bulletin 17B to use the so-called weighted skew coefficient in flood frequency analysis to improve the accuracy of the estimate. The weighted skew is estimated by weighting the station skew and generalized (regional) skew coefficients inversely proportional to their mean square errors.

In the absence of detailed studies, the generalized skew coefficient for sites in the United States can be read from Plate 1 in the Bulletin. Since this map was developed almost 30 years ago, and the mean square error (MSE) of estimates is not available for individual regions but only for the country as a whole (MSE = 0.302), we performed a study for the State of Utah to improve estimates of the skew. For this study we selected all sites that had at least 30 years of record and were located between 37° and 44° North Latitude and 108° and 115° West Longitude. The site-specific skew estimates were plotted on a map of the region. A combination of linear and a bicubic interpolation technique were used to develop a gridded skew map and to construct a contour map (Figure 4). The mean square error to be used with estimates from this map is 0.20 (0.197). These values were used to calculate a weighted skew for each site.

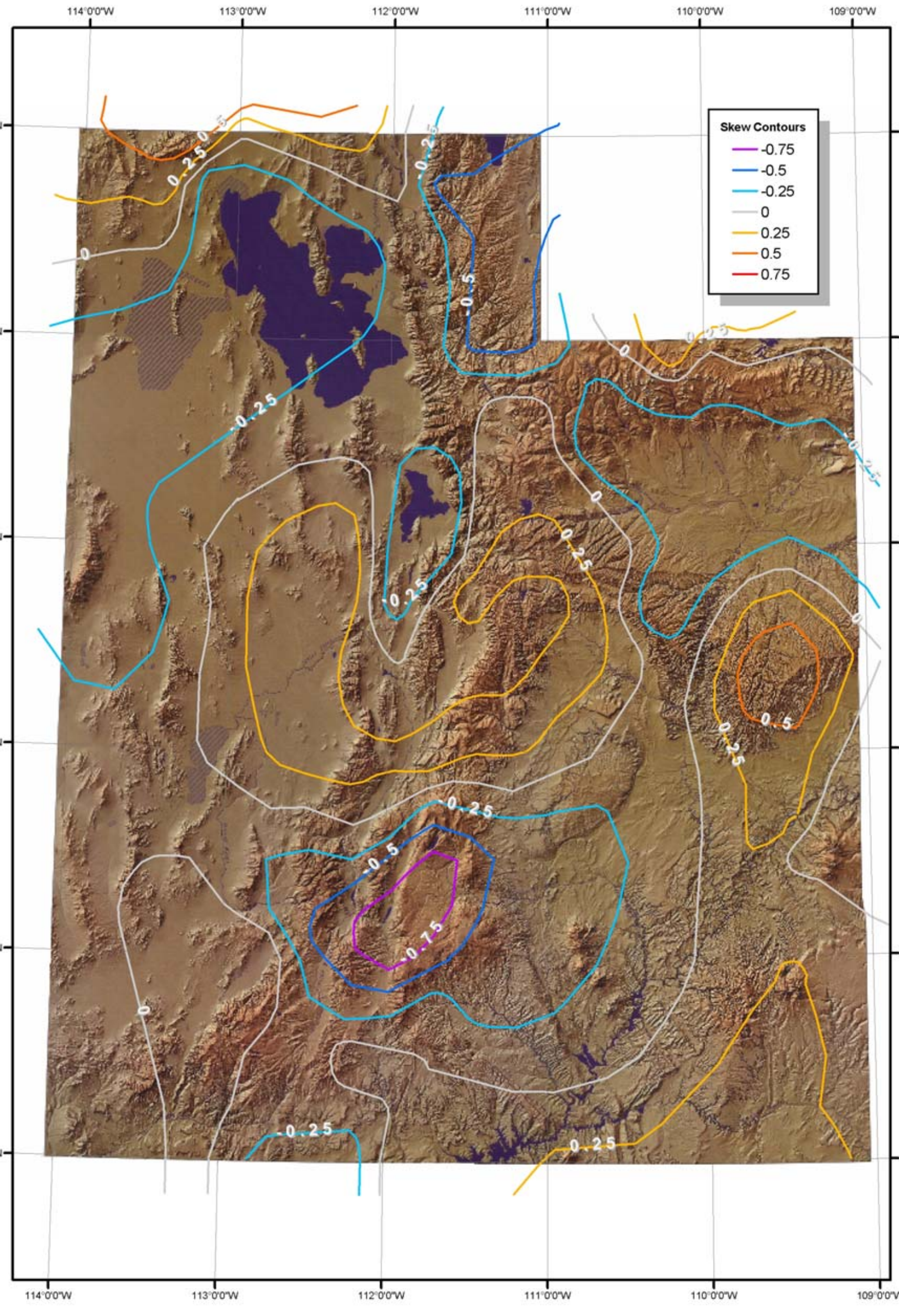

Figure 4. Skew map for the state of Utah. Mean square error for the map is 0.2. (Topographic map from http://rockyweb.cr.usgs.gov/outreach/mapcatalog/images/topography/utah_sr_11x14.pdf)

4. SINGLE-SITE FREQUENCY ANALYSIS

The flow magnitudes for the 2-, 5-, 10-, 25-, 50- and 100-year return periods were estimated using Log Pearson Type III distribution, which is recommended distribution for flood frequency analysis in the United States. The 500-year flood estimates are also given in the Table 5, since there is a need for estimates of flood discharges having return periods on the order of 500 years. For example, the Federal Highway Administration recommends that bridge scour susceptibility be evaluated using an estimate of the 500-year flood event. However, confidence in the flood estimate deteriorates quickly for large return periods, and especially 500-year flow numbers have to be used with caution. The ratios of 500-year events and 100-year events for the sites in the study area varied between 1.1 and 1.7. On average, 500-year events have 25% higher magnitude than 100-year events.

The frequency curve estimated from a record represents some "average" estimate of the true population curve. Having determined the frequency curve, it is necessary to determine its adequacy. Generally, confidence in the estimate for large return periods is low, especially when the sample size is small. Bulletin 17B provides an approximate solution for developing confidence intervals on a frequency curve. The two-sided 90% confidence intervals (or 95% one-sided confidence limits) were calculated for the sites in the study area; they are shown in Table 6 for selected return periods. The numbers in the table are the percent increase or decrease relative to the "average" estimate of the flood frequency. As can be seen from the table, for some sites in the area (usually with short records, e.g., sites 09286100, 10019700 and 10130000), upper limits of the 90% confidence interval are more than 200 percent larger than the "average" estimate for some recurrence intervals, which emphasizes the speculative nature of peak discharge estimates for large return period flow events.

Table 5. Flow rates for selected return periods, as estimated using LP3 distribution.

Site ID	Sample size	Peak discharge (cfs) for indicated recurrence intervals (yrs)						
		2	5	10	25	50	100	500
09273000	21	706	884	984	1096	1170	1238	1377
09273500	19	76	108	127	148	163	176	202
09274000	10	1232	1429	1528	1629	1691	1744	1843
09275000	25	480	685	803	934	1019	1095	1245
09275500	46	448	611	702	800	862	917	1024
09276000	36	51	72	85	104	118	132	168
09280400	19	76	101	117	136	150	164	195
09286100	12	52	122	187	290	381	485	778
10010400	13	561	688	762	846	903	956	1069
10011500	59	1866	2383	2689	3044	3289	3519	4016
10012000	19	389	544	643	766	854	941	1139
10015700	38	333	550	716	949	1139	1344	1878
10019700	17	45	84	116	161	198	239	345
10020500	20	1630	2161	2466	2809	3037	3246	3675
10021000	27	244	357	421	492	537	577	653
10023000	40	61	114	152	199	233	266	338
10104700	32	434	742	973	1288	1539	1800	2455
10104900	21	519	699	821	980	1101	1225	1527
10105000	13	319	524	675	880	1041	1208	1627
10109001	82	1115	1481	1692	1931	2091	2238	2541
10111700	11	141	207	251	307	348	388	480
10113500	82	472	821	1069	1391	1632	1874	2433
10128000	11	567	730	824	929	999	1063	1194
10128200	10	199	226	240	255	265	273	289
10128500	97	1845	2441	2779	3154	3402	3626	4080
10130000	13	137	246	321	415	483	549	692
10131000	75	538	869	1078	1323	1491	1647	1968
10132500	28	233	413	554	753	915	1089	1540
10135000	26	269	359	413	478	524	567	663
10137500	42	846	1245	1500	1809	2030	2242	2711
10137680	11	91	120	137	159	175	190	223
10137780	10	470	571	634	708	762	813	930
10139300	36	103	224	331	498	644	808	1264
10141500	18	19	35	47	63	77	92	129
10142000	34	153	253	329	435	521	613	851
10143000	20	14	24	31	41	49	56	74
10143500	31	14	27	39	59	77	99	167
10145000	20	44	82	113	157	193	232	334
10153800	31	416	546	623	711	770	826	944
10154000	10	180	204	216	230	239	246	262
10158500	11	124	159	180	205	221	237	270
10160800	10	108	149	174	205	228	249	297
10164500	68	335	484	575	679	751	817	956
10165500	19	214	296	352	422	476	529	657
10167500	51	387	512	595	698	775	851	1032
10168500	59	379	500	580	682	759	836	1020
10170000	61	51	74	91	114	132	150	196
10172000	55	26	47	64	89	112	137	207
10172200	38	16	32	47	70	91	115	185
10172500	71	65	99	121	151	173	194	246

Table 6. 90% confidence intervals given as percentage increase/decrease relative to frequency estimates from Table 5.

Site ID	Sample size	Peak discharge (cfs) for indicated recurrence intervals (yrs)						
		2	5	10	25	50	100	500
09273000	21	90 - 111	90 - 115	89 - 119	88 - 122	87 - 124	86 - 127	84 - 131
09273500	19	84 - 121	83 - 128	82 - 134	80 - 140	79 - 144	78 - 148	76 - 155
09274000	10	90 - 112	90 - 118	89 - 122	88 - 126	88 - 128	87 - 131	86 - 135
09275000	25	85 - 118	85 - 124	83 - 128	82 - 133	81 - 136	80 - 139	79 - 143
09275500	46	90 - 111	90 - 114	89 - 116	88 - 119	87 - 120	86 - 122	85 - 124
09276000	36	90 - 111	89 - 115	88 - 118	86 - 123	85 - 126	83 - 129	81 - 136
09280400	19	87 - 115	87 - 120	86 - 125	84 - 131	83 - 135	81 - 139	79 - 148
09286100	12	59 - 171	60 - 215	57 - 254	53 - 309	50 - 351	48 - 394	43 - 497
10010400	13	89 - 113	89 - 119	88 - 123	86 - 129	85 - 133	84 - 136	82 - 143
10011500	59	94 - 107	93 - 109	92 - 110	91 - 112	91 - 113	90 - 115	89 - 117
10012000	19	85 - 118	85 - 124	84 - 130	82 - 137	80 - 142	79 - 147	76 - 157
10015700	38	85 - 117	84 - 123	83 - 128	80 - 135	78 - 140	77 - 145	73 - 156
10019700	17	73 - 138	73 - 155	70 - 170	67 - 190	65 - 204	63 - 219	58 - 251
10020500	20	87 - 115	87 - 121	86 - 125	84 - 130	83 - 133	82 - 135	81 - 141
10021000	27	85 - 119	84 - 125	83 - 129	81 - 134	80 - 137	80 - 139	78 - 143
10023000	40	81 - 125	79 - 133	77 - 139	75 - 145	74 - 149	73 - 153	71 - 161
10104700	32	82 - 122	82 - 129	80 - 135	77 - 143	75 - 149	74 - 155	71 - 166
10104900	21	88 - 114	88 - 119	86 - 124	84 - 130	83 - 135	81 - 139	78 - 149
10105000	13	75 - 134	75 - 151	73 - 166	70 - 185	68 - 199	66 - 213	62 - 244
10109001	82	94 - 107	93 - 109	92 - 110	91 - 112	91 - 113	90 - 114	89 - 116
10111700	11	78 - 129	78 - 145	77 - 157	74 - 173	72 - 184	71 - 195	67 - 219
10113500	82	88 - 114	87 - 117	85 - 120	84 - 124	83 - 126	82 - 129	80 - 133
10128000	11	84 - 119	85 - 129	84 - 136	82 - 143	81 - 149	80 - 154	78 - 163
10128200	10	91 - 110	91 - 115	91 - 118	90 - 122	89 - 124	89 - 127	88 - 131
10128500	97	94 - 106	93 - 108	93 - 109	92 - 111	91 - 111	91 - 112	90 - 114
10130000	13	70 - 147	70 - 170	68 - 187	65 - 208	63 - 222	62 - 234	59 - 260
10131000	75	89 - 113	87 - 117	86 - 119	85 - 122	84 - 124	83 - 125	82 - 128
10132500	28	80 - 125	80 - 134	77 - 142	75 - 152	73 - 159	71 - 166	67 - 182
10135000	26	89 - 113	89 - 117	87 - 120	86 - 125	85 - 127	84 - 130	82 - 136
10137500	42	88 - 113	88 - 118	86 - 121	85 - 125	84 - 127	83 - 130	81 - 135
10137680	11	84 - 119	85 - 129	83 - 137	81 - 147	80 - 154	78 - 161	75 - 176
10137780	10	88 - 114	88 - 121	87 - 127	86 - 135	84 - 140	83 - 146	81 - 158
10139300	36	77 - 131	76 - 141	73 - 151	70 - 163	68 - 172	66 - 180	62 - 198
10141500	18	75 - 134	75 - 149	72 - 162	69 - 178	67 - 191	65 - 202	61 - 228
10142000	34	84 - 119	83 - 125	82 - 131	79 - 138	77 - 144	76 - 149	72 - 161
10143000	20	77 - 131	76 - 144	74 - 154	71 - 167	70 - 175	68 - 183	65 - 200
10143500	31	79 - 126	79 - 135	76 - 144	73 - 157	70 - 167	67 - 178	62 - 202
10145000	20	75 - 134	74 - 149	72 - 161	69 - 178	67 - 189	65 - 201	61 - 226
10153800	31	90 - 111	90 - 115	89 - 117	87 - 121	86 - 123	86 - 125	84 - 129
10154000	10	92 - 110	92 - 114	91 - 117	90 - 121	90 - 124	89 - 126	88 - 130
10158500	11	85 - 119	85 - 128	84 - 135	82 - 143	81 - 149	80 - 155	78 - 166
10160800	10	80 - 125	81 - 139	80 - 150	77 - 163	76 - 173	74 - 182	71 - 202
10164500	68	91 - 110	90 - 113	89 - 115	88 - 117	87 - 119	86 - 120	85 - 123
10165500	19	86 - 116	86 - 123	84 - 129	82 - 136	81 - 141	79 - 147	76 - 158
10167500	51	93 - 108	92 - 110	91 - 113	90 - 115	89 - 117	88 - 119	86 - 123
10168500	59	93 - 107	93 - 109	92 - 111	90 - 114	89 - 116	88 - 117	86 - 121
10170000	61	91 - 110	90 - 113	89 - 116	87 - 119	86 - 122	85 - 124	82 - 130
10172000	55	86 - 117	85 - 121	83 - 126	80 - 133	78 - 138	77 - 142	73 - 153
10172200	38	79 - 126	78 - 135	76 - 144	72 - 155	70 - 163	68 - 171	64 - 189
10172500	71	90 - 111	90 - 114	88 - 116	87 - 119	86 - 121	85 - 123	83 - 127

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5. REGIONAL FLOOD FREQUENCY ANALYSIS

In this study we used the classical multiplicative multiple regression model of the following form: $Q_T = a\, X_1^b\, X_2^c\, X_3^d \ldots$; in which Q_T is the peak discharge for the selected return period T (from Table 5), X_i are watershed and meteorological characteristics selected as explanatory variables, and a, b, c... are regression parameters that need to be calibrated. Since it is unknown in advance what watershed or meteorological characteristics may have significant impact on flood frequency estimates, a number of parameters were calculated and investigated as possible predictors of T-year discharges.

5.1 Watershed Characteristics Acquisition

a) Geometric Characteristics

The Watershed Modeling System (WMS) computer program, which utilizes digital terrain data to delineate watershed and sub-basin boundaries, was used to calculate watershed parameters that were investigated as possible predictors of T-year discharges. The geometric characteristics were obtained by, first acquiring digital elevation maps (DEM) from the USGS National Elevation Dataset (NED) website (http://seamless.usgs.gov/). NED has a resolution of one arc-second (approximately 30 meters). The horizontal projection is geographical NAD83, and the elevation is in decimal meters.

These DEMs were then inserted into the WMS program, where each gaging station was plotted according to their decimal latitude and longitude location (given in NAD83 projection) obtained from the USGS Surface Water website (http://waterdata.usgs.gov/nwis/sw). WMS was then used to calculate eleven geometric characteristics that were investigated as possible predictors of T-year flows (see Table 7) for each watershed for which a flood frequency number was estimated. The following list shows selected geometric parameters, their definition and units of measurement.

Parameter	Definition and units
Area	The area of the basin in square miles.
Basin Average Elevation	The mean basin elevation in feet.
Basin Length	Length of the entire basin in miles.
Basin Slope	The average basin slope.
Basin Perimeter	Distance of the basin perimeter from the outlet point in miles.
Basin Shape Factor	Basin length divided by the basin width.
Max Stream Length	The maximum stream length within the basin in miles.
Max Stream Slope	The slope of the *Max Stream Length*.
Overland Flow	The average overland flow distance within the basin in miles.
North Facing	The percentage of the basin whose aspect is directed north.
South Facing	The percentage of the basin whose aspect is directed south.

b) Soil type and land use data

Both, the soil type and land use GIS datasets, were obtained from the Environmental Protection Agency website (http://www.epa.gov/ost/ftp/basins/gis_data/huc/). Datasets were imported into WMS and projected in the NAD83 where the soil type (see Table 8) and the land use characteristics (Table 9) were determined. Soils were classified according to the Natural Resources Conservation Service's hydrologic soil group classification system as Type A, B, C and D soils (http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-wintr55.html). Land use characteristics were classified as forest lands, pasture and agriculture lands, rangelands, urban (residential and commercial), lakes and reservoirs, and other (that included all other land types).

5.2. Precipitation Data

Precipitation data for the sites in the study area were obtained from the National Weather Service Precipitation Frequency Data Server (http://hdsc.nws.noaa.gov/hdsc/pfds/). Daily precipitation amounts for selected return periods are given in Table 10.

Table 7. Geometric characteristics.

Site ID	Basin						Max. Stream		Overland	Facing	
	Area (mi^2)	Elevation (ft)	Length (mi)	Slope	Perimeter (mi)	Shape	Length (mi)	Slope	Flow (mi)	N (%)	S (%)
09273000	37.52	10179	9.10	0.25	42.32	2.21	9.83	0.05	0.81	41	59
09273500	7.36	10069	4.96	0.39	18.89	3.34	3.80	0.12	0.83	35	65
09274000	79.72	9828	14.47	0.29	68.27	2.63	17.21	0.04	0.79	41	59
09275000	43.17	9161	11.71	0.24	44.27	3.18	12.55	0.03	0.76	54	46
09275500	61.60	8861	16.41	0.25	56.51	4.37	18.10	0.02	0.74	50	50
09276000	10.60	9158	6.00	0.27	21.75	3.40	5.90	0.05	0.78	32	68
09280400	3.06	9030	2.81	0.18	11.36	2.59	1.58	0.07	0.81	52	48
09286100	31.34	8655	9.56	0.25	37.05	2.92	12.08	0.03	0.80	51	49
10010400	35.24	10380	9.93	0.40	37.87	2.80	10.64	0.03	0.72	58	42
10011500	57.12	9222	12.75	0.14	49.62	2.84	13.23	0.02	0.74	61	39
10012000	54.32	9234	12.07	0.16	46.87	2.68	13.32	0.03	0.78	58	42
10015700	61.19	7990	10.69	0.10	49.07	1.87	12.65	0.03	0.77	74	26
10019700	8.96	7309	5.20	0.17	18.80	3.02	4.92	0.02	0.67	57	43
10020500	846.10	7911	57.30	0.14	281.43	3.88	75.03	0.01	0.70	59	41
10021000	61.40	7913	13.36	0.27	51.14	2.91	15.18	0.02	0.61	51	49
10023000	50.80	7387	11.31	0.19	42.87	2.52	12.41	0.02	0.66	50	50
10104700	62.12	6735	10.35	0.31	46.90	1.72	10.40	0.04	0.76	60	40
10104900	56.80	7334	12.45	0.29	57.33	2.73	15.72	0.03	0.67	54	46
10105000	69.11	7214	14.22	0.31	63.62	2.92	17.91	0.03	0.68	55	45
10109001	215.56	7555	26.42	0.33	108.55	3.24	37.72	0.02	0.64	47	53
10111700	78.00	7377	9.72	0.26	56.50	1.21	11.49	0.05	0.63	55	45
10113500	262.92	7160	19.86	0.29	117.71	1.50	27.73	0.02	0.64	51	49
10128000	33.65	9331	8.31	0.35	36.75	2.05	7.99	0.04	0.68	60	40
10128200	19.27	8733	6.52	0.38	29.86	2.21	6.32	0.05	0.76	62	38
10128500	162.11	9053	18.80	0.34	83.14	2.18	24.50	0.03	0.71	54	46
10130000	27.47	7130	10.85	0.17	41.73	4.28	12.54	0.02	0.78	61	39
10131000	248.30	7541	23.11	0.22	100.75	2.15	35.67	0.02	0.71	59	41
10132500	125.46	7319	13.73	0.29	73.96	1.50	16.32	0.02	0.61	47	53
10135000	28.27	7200	7.06	0.40	35.85	1.77	7.26	0.04	0.70	58	42
10137500	137.73	7218	14.64	0.32	76.21	1.56	16.11	0.03	0.63	49	51
10137680	5.99	7115	3.77	0.40	14.17	2.38	3.07	0.07	0.71	49	51
10137780	31.36	7301	9.60	0.31	39.69	2.94	11.85	0.04	0.69	44	56
10139300	11.15	6574	4.81	0.34	19.22	2.08	3.83	0.07	0.85	61	39
10141500	2.44	7609	2.63	0.53	8.98	2.84	1.57	0.17	0.79	45	55
10142000	10.04	7470	5.85	0.41	21.40	3.40	6.23	0.07	0.63	51	49
10143000	2.16	7067	3.51	0.45	10.95	5.69	2.45	0.16	0.54	32	68
10143500	3.17	6939	3.83	0.47	12.58	4.64	3.22	0.13	0.40	46	54
10145000	8.87	7397	5.12	0.44	18.03	2.96	4.81	0.11	0.63	47	53
10153800	24.75	9452	9.30	0.26	30.46	3.50	9.12	0.05	0.68	37	63
10154000	8.02	9319	5.38	0.27	18.52	3.61	4.94	0.07	0.62	33	67
10158500	70.02	7119	11.98	0.26	50.81	2.05	13.19	0.04	0.97	58	42
10160800	12.28	8104	4.88	0.51	23.10	1.94	4.73	0.10	0.72	46	54
10164500	51.19	8473	10.03	0.48	47.29	1.97	11.52	0.05	0.67	47	53
10165500	9.64	8834	5.42	0.47	19.64	3.04	4.01	0.16	0.80	32	68
10167500	27.39	8851	10.46	0.56	40.14	3.99	11.51	0.07	0.66	57	43
10168500	50.00	8546	12.04	0.51	47.29	2.90	14.48	0.05	0.66	56	44
10170000	21.74	7691	9.62	0.55	35.24	4.26	10.58	0.06	0.67	56	44
10172000	18.52	6430	8.16	0.41	27.74	3.59	8.80	0.04	0.77	39	61
10172200	7.24	6808	4.39	0.51	16.40	2.66	3.48	0.06	0.57	41	59
10172500	17.06	6898	9.55	0.48	31.94	5.34	10.08	0.06	0.60	42	58

Table 8. Soil characteristics.

Site ID	Type A (mi^2)	Type B (mi^2)	Type C (mi^2)	Type D (mi^2)
09273000	0.00	0.00	23.40	14.10
09273500	0.00	0.00	1.05	6.32
09274000	0.00	0.00	50.85	28.81
09275000	41.28	1.87	0.00	0.00
09275500	0.00	59.41	0.00	2.08
09276000	0.00	3.89	2.25	4.45
09280400	0.00	3.05	0.00	0.00
09286100	0.00	31.31	0.00	0.00
10010400	18.28	16.96	0.00	0.00
10011500	0.00	0.00	48.52	8.58
10012000	0.00	0.00	42.56	11.78
10015700	0.00	37.74	17.72	5.58
10019700	0.00	8.93	0.00	0.00
10020500	0.00	342.05	239.38	262.55
10021000	0.00	6.98	21.93	32.45
10023000	0.00	0.00	20.43	30.31
10104700	0.00	19.49	42.13	0.58
10104900	0.00	20.05	36.67	0.00
10105000	0.00	20.04	46.88	1.73
10109001	0.00	122.07	87.22	6.19
10111700	0.00	45.17	32.80	0.00
10113500	0.00	156.19	102.94	3.82
10128000	0.19	23.75	9.25	0.44
10128200	0.10	4.60	14.54	0.00
10128500	10.07	83.54	64.86	3.40
10130000	12.30	3.90	11.16	0.00
10131000	11.19	36.41	199.92	0.00
10132500	0.00	83.47	40.83	0.22
10135000	0.00	24.76	3.44	0.00
10137500	0.00	106.41	9.37	21.96
10137680	0.00	2.75	0.00	3.24
10137780	0.00	24.45	2.88	3.98
10139300	0.00	4.27	4.42	2.44
10141500	0.00	0.00	2.43	0.00
10142000	0.00	4.19	5.84	0.00
10143000	0.00	1.72	0.45	0.00
10143500	0.00	2.31	0.85	0.00
10145000	0.75	0.00	8.01	0.00
10153800	0.00	10.16	14.49	0.01
10154000	0.00	3.20	4.81	0.00
10158500	0.00	65.25	0.00	4.71
10160800	4.17	8.08	0.00	0.00
10164500	40.18	6.60	0.00	0.94
10165500	2.28	0.00	2.40	4.95
10167500	23.76	0.00	0.00	3.61
10168500	26.83	0.00	23.09	0.00
10170000	0.16	0.00	9.82	11.75
10172000	10.89	0.00	7.58	0.00
10172200	6.54	0.00	0.70	0.00
10172500	6.02	0.72	10.30	0.00

Table 9. Land use characteristics.

Site ID	Forest (mi^2)	Rangeland (mi^2)	Pasture (mi^2)	Urban (mi^2)	Lakes (mi^2)	Other (mi^2)
09273000	33.32	0.00	0.00	0.00	0.34	3.86
09273500	6.64	0.00	0.00	0.00	0.00	0.72
09274000	74.19	0.12	0.00	0.00	0.39	5.02
09275000	38.85	4.27	0.00	0.00	0.00	0.05
09275500	51.80	9.66	0.00	0.00	0.00	0.14
09276000	9.94	0.66	0.00	0.00	0.00	0.00
09280400	3.06	0.00	0.00	0.00	0.00	0.00
09286100	25.20	6.11	0.00	0.00	0.00	0.03
10010400	27.38	0.00	0.00	0.00	0.04	7.82
10011500	40.77	16.15	0.11	0.00	0.03	0.06
10012000	49.31	2.68	2.33	0.00	0.00	0.00
10015700	16.70	38.14	6.20	0.00	0.00	0.15
10019700	0.00	8.84	0.00	0.12	0.00	0.00
10020500	235.82	523.84	58.45	7.01	2.69	19.23
10021000	31.94	29.43	0.00	0.00	0.00	0.03
10023000	11.20	39.54	0.01	0.00	0.00	0.05
10104700	16.29	45.43	0.40	0.00	0.00	0.00
10104900	23.28	33.44	0.00	0.00	0.00	0.08
10105000	28.81	39.97	0.00	0.00	0.17	0.16
10109001	155.42	59.46	0.00	0.42	0.10	0.16
10111700	39.54	38.42	0.00	0.00	0.00	0.04
10113500	138.07	124.85	0.00	0.00	0.00	0.00
10128000	31.91	1.34	0.00	0.00	0.00	0.40
10128200	17.13	2.11	0.00	0.00	0.00	0.03
10128500	145.43	11.58	0.00	0.75	0.26	4.09
10130000	3.74	18.22	2.44	2.99	0.00	0.08
10131000	104.75	136.36	4.81	0.33	0.21	1.84
10132500	44.94	80.03	0.00	0.00	0.49	0.00
10135000	14.72	13.48	0.00	0.00	0.00	0.07
10137500	39.77	96.65	0.18	0.04	0.06	1.03
10137680	1.81	4.18	0.00	0.00	0.00	0.00
10137780	5.01	25.93	0.00	0.00	0.00	0.42
10139300	3.37	7.78	0.00	0.00	0.00	0.00
10141500	0.81	1.63	0.00	0.00	0.00	0.00
10142000	4.58	5.46	0.00	0.00	0.00	0.00
10143000	0.00	2.16	0.00	0.00	0.00	0.00
10143500	1.02	2.15	0.00	0.00	0.00	0.00
10145000	0.69	8.15	0.00	0.00	0.00	0.03
10153800	23.49	0.73	0.00	0.00	0.16	0.37
10154000	7.90	0.09	0.00	0.00	0.00	0.03
10158500	24.47	40.39	4.96	0.14	0.00	0.06
10160800	5.70	5.80	0.00	0.31	0.00	0.47
10164500	43.28	7.53	0.00	0.00	0.00	0.38
10165500	4.24	4.90	0.00	0.00	0.00	0.50
10167500	17.48	7.59	0.00	0.00	0.00	2.32
10168500	28.88	17.80	0.00	1.74	0.07	1.51
10170000	13.83	7.91	0.00	0.00	0.00	0.00
10172000	2.23	16.27	0.00	0.02	0.00	0.00
10172200	0.46	6.78	0.00	0.00	0.00	0.00
10172500	4.24	12.77	0.00	0.05	0.00	0.00

Table 10. Daily precipitation amounts for selected return periods.

Site ID	24-hr Precipitation Depth (in)					
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
09273000	1.78	2.41	2.86	3.47	3.95	4.46
09273500	1.58	2.13	2.52	3.06	3.48	3.93
09274000	1.58	2.13	2.52	3.06	3.48	3.93
09275000	1.43	1.91	2.25	2.71	3.06	3.44
09275500	1.24	1.67	1.98	2.38	2.70	3.04
09276000	1.50	2.01	2.38	2.87	3.26	3.67
09280400	1.69	2.22	2.58	3.03	3.36	3.69
09286100	1.27	1.71	2.03	2.45	2.77	3.12
10010400	1.37	1.85	2.20	2.67	3.04	3.43
10011500	1.24	1.67	1.98	2.39	2.72	3.07
10012000	1.26	1.70	2.01	2.44	2.77	3.13
10015700	1.20	1.60	1.80	2.20	2.40	2.75
10019700	1.00	1.40	1.60	1.90	2.20	2.40
10020500	0.99	1.31	1.54	1.84	2.07	2.31
10021000	1.18	1.57	1.84	2.21	2.49	2.78
10023000	1.09	1.44	1.69	2.01	2.27	2.54
10104700	1.77	2.31	2.67	3.16	3.53	3.91
10104900	2.07	2.72	3.16	3.76	4.22	4.69
10105000	2.00	2.61	3.04	3.60	4.04	4.49
10109001	1.47	1.94	2.27	2.70	3.04	3.40
10111700	1.29	1.70	1.99	2.38	2.68	2.97
10113500	1.75	2.31	2.70	3.22	3.63	4.04
10128000	1.61	2.17	2.58	3.12	3.56	4.02
10128200	1.36	1.83	2.16	2.60	2.96	3.32
10128500	1.30	1.75	2.06	2.48	2.81	3.16
10130000	1.35	1.79	2.10	2.51	2.84	3.17
10131000	1.15	1.55	1.84	2.23	2.54	2.87
10132500	1.53	2.05	2.42	2.91	3.30	3.71
10135000	1.72	2.22	2.57	3.01	3.34	3.68
10137500	2.00	2.59	3.00	3.53	3.93	4.35
10137680	3.09	4.00	4.61	5.41	6.02	6.63
10137780	2.21	2.87	3.32	3.91	4.35	4.81
10139300	1.98	2.55	2.94	3.45	3.84	4.23
10141500	2.05	2.66	3.07	3.61	4.03	4.44
10142000	1.97	2.55	2.95	3.47	3.87	4.26
10143000	1.83	2.36	2.73	3.20	3.56	3.93
10143500	1.76	2.27	2.62	3.07	3.42	3.77
10145000	1.89	2.45	2.83	3.32	3.70	4.08
10153800	1.45	1.95	2.31	2.80	3.18	3.58
10154000	1.51	2.03	2.41	2.93	3.33	3.76
10158500	1.43	1.90	2.24	2.68	3.03	3.39
10160800	1.75	2.33	2.74	3.28	3.71	4.16
10164500	1.91	2.47	2.84	3.34	3.72	4.09
10165500	1.67	2.16	2.49	2.93	3.25	3.58
10167500	1.58	2.04	2.35	2.76	3.07	3.38
10168500	1.63	2.10	2.43	2.84	3.16	3.48
10170000	1.58	2.04	2.36	2.77	3.08	3.39
10172000	1.54	1.98	2.29	2.69	2.98	3.29
10172200	1.72	2.22	2.56	3.01	3.35	3.69
10172500	1.55	2.00	2.31	2.71	3.01	3.32

5.3 Regional Flood Frequency Equations

Backward stepwise regression analysis was used to select the variables to be included in a multiple regression model. This type of regression approach initially considers all chosen explanatory variables as predictors of T-year discharge. Then the variables with the smallest significance are removed until only the statistically significant terms remain. The variables used in the analysis have to be independent of each other, since when a dependency exists between two predictor variables, the presence of one variable masks the effect of another. Many variables initially considered as potential predictors of T-year floods were highly correlated (correlation implies linear dependence) among themselves. As could be expected, 24-hour precipitation estimates for selected return periods had correlation coefficients greater than 0.98. Strong linear dependence was also found among many geometric characteristics. Correlation coefficients among area, basin length, basin perimeter and streamflow length parameters were all above 0.95. Similarly, basin slope and streamflow slope had a correlation coefficient of 0.99. The chosen set of explanatory variables used in regression analysis included: basin area, mean basin elevation, basin slope, basin shape factor, overland flow, and north facing area from geometric characteristics; Type B, C and D soil types; rangeland and forest land use characteristics; and 2-year 24-hour precipitation depths.

The results of the regression analysis indicated that among all variables considered only drainage area was statistically significant term for larger return periods. The standard error of estimate for more frequent events ($T < 25$ years) markedly reduced when the mean basin elevation parameter was retained in prediction equations. The stratification of data in low/middle and high elevation regions did not reduce standard errors.

On the other hand, a geographic plot of residuals (defined as relative differences between discharge values calculated using the regression equation and discharge values estimated from frequency analysis) on a map for a selected return period showed clear spatial patterns (see Figure 6 for a map of residuals for a 100-year return period). The geographic patterns of residuals were consistent for all return periods. The prediction equations created considerable positively-biased estimates for several sites in the region (10023000 and 10111700 located above the Weber River basin; 10158500 below the basin; and four sites located near 40º47' latitude and 111º48' longitude: 10172000, 10170000, 10168500 and 10167500). We examined streamflow records for those sites one more time. For site 10023000 it was observed that the 1957 peak discharge of 337 cfs was almost 3 times higher than any other flood event on record. The related gage height of 3.75 ft, however, was in line with common recorded heights that were associated with streamflow amounts between 9 and 132 cfs. It is possible that the 1957 discharge number is a misprint and that it should be reduced by a magnitude of 10 (i.e., 33.7 cfs). Site 10111700 had a discontinuous record (1966 - 1969 and 1986 - 1992 periods) and only 11 years of data. Similarly, site 10158500 had data for 1939 -1950 period only. Finally, for all four sites located near 40º47' latitude and 111º48' longitude, the majority of recorded annual peak flows were not instantaneous peaks but maximum daily averages, and the record for all four sites ended in 1963.

Once these seven sites were removed from the data set, new prediction equations were calculated for the region. As can be seen from Figure 7 for a 100-year storm event, the magnitude of residuals decreased significantly. This time, no obvious consistent geographic patterns in residuals were found. The (standardized) standard error of prediction was calculated, and it is given in Table 11 together with the developed regional equations. Two alternative regional flood frequency equations are given in the table; the first one ("Alternative 1") includes both, drainage area and mean basin elevation as significant explanatory variables and the second one ("Alternative 2") includes only drainage area as a predictor variable.

The flood frequency equations from Table 11 are applicable for uregulated, ungaged sites in the Weber River basin with characteristics that fall within the range of explanatory variables for the gaged sites in the region that were used to develop prediction equations. Therefore, they are most relevant to sites with drainage areas between approximately 2 and 250 mi^2 and mean basin elevation between 6,500 and 10,000 ft.

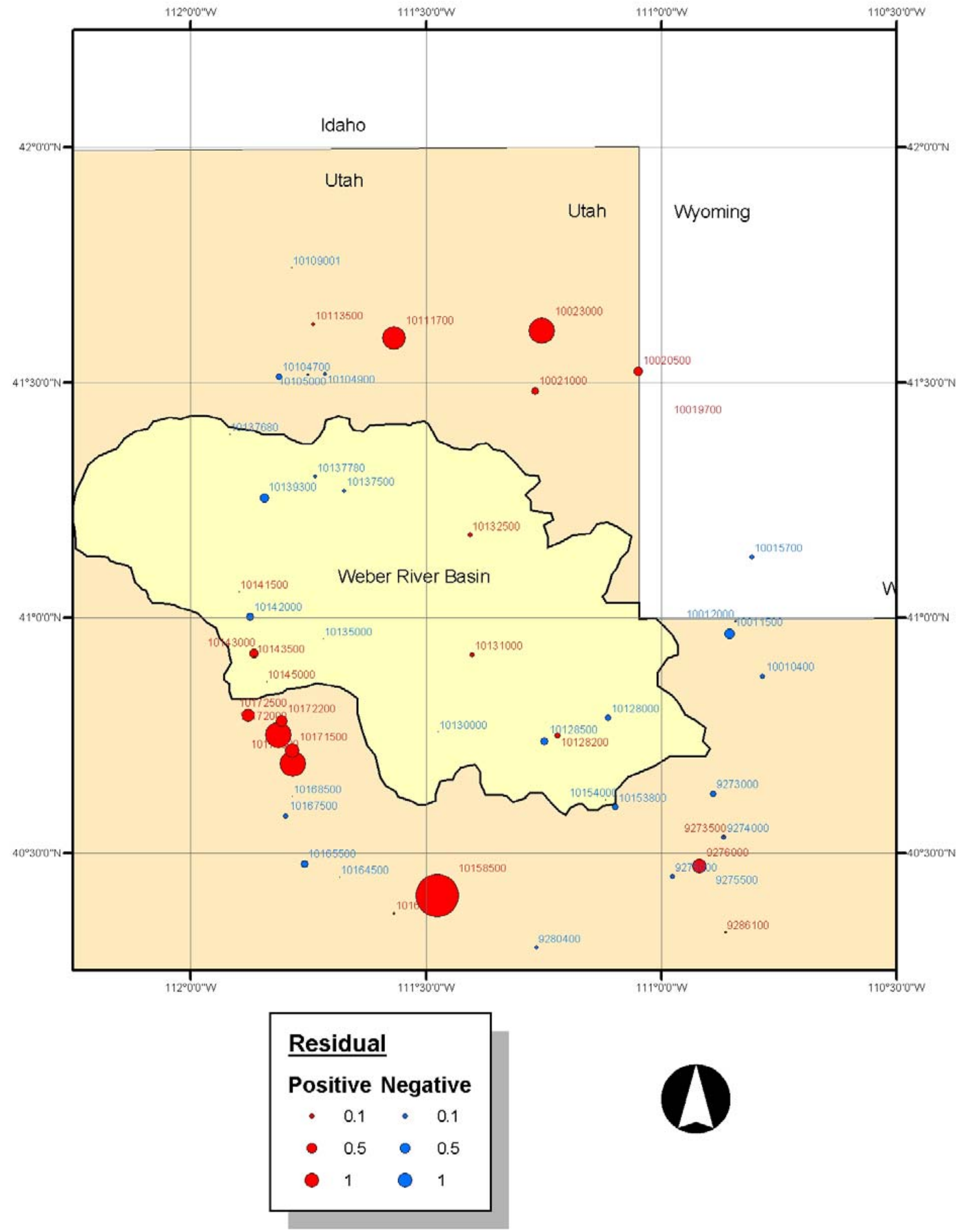

Figure 6. Map of residuals for a 100-yr prediction equation with drainage area as only predictor. Red dots indicate positive biases (i.e., prediction equations overestimates discharge) and blue dots indicate negative biases.

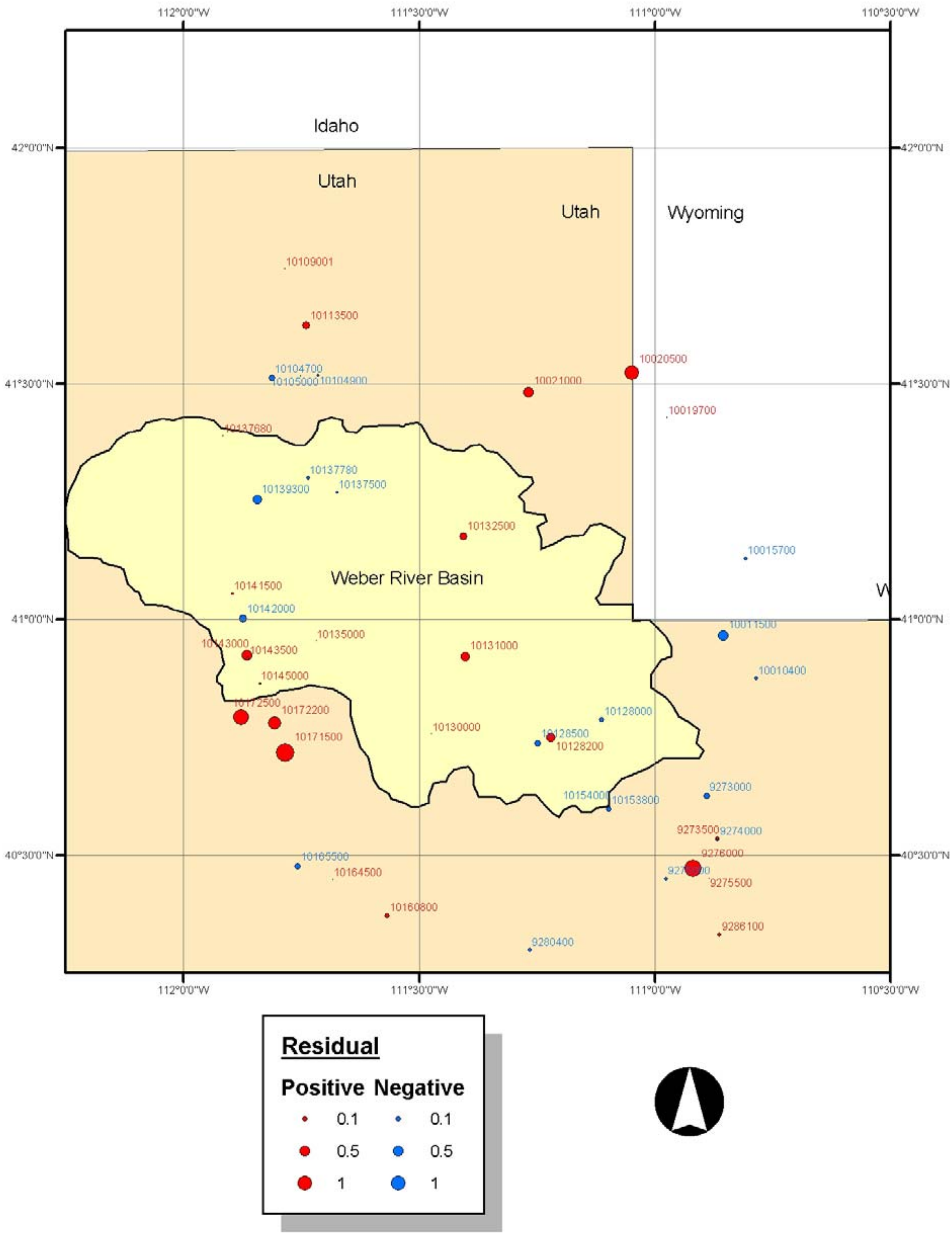

Figure 7. Same as in Figure 6 after seven sites were removed from the data set.

Table 11. Flood frequency equations for T-year peak discharges (cfs) for ungaged, unregulated watersheds in Weber River basin with drainage areas between approximately 2 and 250 mi^2 and mean basin elevation between 6,500 and 10,000 ft.

Return Period T (yr)	Alternative 1		Alternative 2	
	Flood-frequency equation	Se	Flood-frequency equation	Se
5	$Q = 0.174\ A^{0.7665}\ (E/1000)^{2.3684}$	66	$Q = 23.377\ A^{0.7794}$	76
10	$Q = 0.546\ A^{0.7515}\ (E/1000)^{1.9399}$	58	$Q = 30.228\ A^{0.7620}$	65
25	$Q = 1.866\ A^{0.7326}\ (E/1000)^{1.4793}$	52	$Q = 39.855\ A^{0.7407}$	57
50	$Q = 4.145\ A^{0.7186}\ (E/1000)^{1.1813}$	51	$Q = 47.777\ A^{0.7250}$	54
100	$Q = 8.449\ A^{0.7061}\ (E/1000)^{0.9139}$	50	$Q = 55.995\ A^{0.7111}$	52

where: Q - peak flow (cfs)
A - drainage area (mi^2)
E – mean basin elevation (ft)
Se – average standard error of prediction (%)

5.4 Comparison with Most Recent USGS National Flood Frequency Equations

Finally, regional flood estimates from this study and estimates from current USGS regional equations were compared to at-site values obtained from the frequency analysis. The most recent flood frequency study for the state of Utah done by the US Geological Survey includes data through water year 1986 (Blakemore et al., 1994). Although 16 additional years were available for frequency analysis in this study, and prediction equations were calibrated to updated flood frequency magnitudes, the prediction accuracy did not change significantly for the following reasons: (a) there were no major flood events in the region during the last 16 years that could significantly affect flood frequency estimates, and (b) both studies ended up using drainage area and mean basin elevation as predictors of T-year discharges. The results of the comparison for the sites inside the study area are given in Table 12.

Table 12. Comparison of regional flood estimates from this study and estimates from current USGS regional equations; (1) indicates flood frequency estimates, (2) is percent error of regional estimates from this study; and (3) is percent error for current USGS estimates.

Site ID	Return Period (years)											
	10			25			50			100		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
9273500	127	70	68	148	66	68	163	63	71	176	62	73
9274000	1528	-19	-33	1629	-17	-28	1691	-15	-22	1744	-14	-17
9275000	803	-15	-25	934	-17	-23	1019	-17	-19	1095	-17	-17
9275500	702	18	3	800	20	9	862	22	17	917	24	22
9276000	85	178	175	104	168	171	118	162	174	132	157	171
9280400	117	-23	-15	136	-19	-11	150	-17	-7	164	-15	-5
9286100	187	156	137	290	96	86	381	66	64	485	43	44
10010400	762	-3	-15	846	-4	-13	903	-6	-10	956	-7	-8
10011500	2689	-68	-73	3044	-68	-71	3289	-68	-70	3519	-68	-69
10012000	643	27	11	766	22	10	854	18	13	941	15	13
10015700	716	-5	-15	949	-13	-19	1139	-19	-21	1344	-23	-24
10019700	116	16	24	161	10	18	198	6	16	239	2	11
10020500	2466	94	43	2809	98	55	3037	99	68	3246	101	77
10021000	421	58	43	492	65	54	537	71	66	577	77	76
10104700	973	-50	-52	1288	-50	-51	1539	-50	-50	1800	-50	-50
10104900	821	-34	-39	980	-30	-33	1101	-28	-29	1225	-26	-26
10105000	675	-10	-17	880	-12	-17	1041	-14	-15	1208	-15	-16
10109001	1692	-8	-23	1931	-1	-14	2091	3	-6	2238	6	0
10113500	1069	53	27	1391	46	27	1632	42	30	1874	39	30
10128000	824	-29	-36	929	-28	-33	999	-27	-29	1063	-27	-27
10128200	240	41	35	255	58	55	265	70	73	273	81	87
10128500	2779	-35	-48	3154	-36	-46	3402	-36	-43	3626	-37	-41
10130000	321	-7	-8	415	-7	-6	483	-6	-2	549	-4	-1
10131000	1078	61	32	1323	59	37	1491	59	44	1647	60	49
10132500	554	77	55	753	62	47	915	53	45	1089	45	40
10135000	413	-25	-26	478	-16	-16	524	-10	-7	567	-4	-1
10137500	1500	-32	-41	1809	-29	-36	2030	-27	-31	2242	-26	-29
10137680	137	-31	-23	159	-21	-12	175	-13	-2	190	-5	5
10137780	634	-46	-47	708	-38	-38	762	-32	-31	813	-27	-25
10139300	331	-61	-58	498	-64	-61	644	-66	-63	808	-68	-65
10141500	47	16	36	63	15	33	77	12	31	92	10	26
10142000	329	-54	-51	435	-54	-52	521	-55	-51	613	-56	-52
10143000	31	39	69	41	44	72	49	48	76	56	55	80
10143500	39	43	69	59	29	51	77	22	42	99	13	29
10145000	113	21	29	157	14	22	193	10	20	232	6	15
10153800	623	-24	-30	711	-24	-28	770	-23	-24	826	-23	-22
10154000	216	-8	-8	230	1	4	239	8	14	246	15	23
10160800	174	20	21	205	26	30	228	31	38	249	35	43
10164500	575	15	3	679	16	8	751	16	13	817	17	16
10165500	352	-42	-41	422	-42	-40	476	-42	-39	529	-42	-38
10172200	47	112	137	70	94	116	91	82	104	115	72	89
10172500	121	61	67	151	72	80	173	80	92	194	89	100

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Watershed Modeling System - WMS, software package, available from www.ems_i.com/home.html.

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Appendix 1

135 USGS gaging sites located in study area. Sites used in the frequency analysis are highlighted.

Site ID	Name	Comment
9273000	Duchesne R At Provo R Trail Nr Hanna, Utah	
9273500	Hades Creek Near Hanna, Utah	
9274000	Duchesne River (N.Fork) Near Hanna, Utah	High Outlier
9274900	W.F. Duchesne Riv Bel Vat Diversion Nr Hanna, Ut	Insufficient Data
9275000	W F Duchesne River Bl Dry Hollow Nr Hanna, Ut	Low outlier
9275500	West Fork Duchesne River Near Hanna, Ut	4 Low Outliers
9276000	Wolf Creek Above Rhoades Canyon Near Hanna, Ut	2 High Outliers
9276600	W.F. Duchesne River Abv North Fork, Nr Hanna, Ut	Diversion/Regulation
9280400	Hobble Creek At Daniels Summit Near Wallsburg Ut	2 Low Outliers
9286100	Red Creek Above Reservoir, Near Fruitland, Ut	
9286700	Currant Crk Blw Currant Crk Dam, Nr Fruitland, Ut	Diversion/Regulation
9287000	Currant C Bl Red Ledge Hollow Nr Fruitland, Ut	Diversion/Regulation
10010400	East Fk Bear River Nr Evanston, Wyoming	
10011200	West Fork Bear River At Whitney Dam, Nr Oakley, Ut	Diversion/Regulation
10011400	West Fk Bear River Bl Deer Cr Nr Evanston, Wyo	Diversion/Regulation
10011500	Bear River Near Utah-Wyoming State Line	
10012000	Mill Creek At Utah-Wyoming State Line	
10015700	Sulphur Cr.Ab.Res.Bl.La Chapelle Cr.Nr Evanston,Wy	High Outlier
10016900	Bear River At Evanston, Wy	Diversion/Regulation
10017000	Yellow Creek Near Evanston, Wyoming	Diversion/Regulation
10019700	Whitney Canyon Creek Near Evanston, Wy	
10020100	Bear River Above Reservoir, Near Woodruff, Ut	Diversion/Regulation
10020300	Bear River Below Reservoir, Near Woodruff, Ut	Diversion/Regulation
10020500	Bear River Near Woodruff, Utah	
10020900	Woodruff Creek Below Reservoir Nr Woodruff, Utah	Diversion/Regulation
10021000	Woodruff Creek Near Woodruff, Utah	
10021500	Birch Cr Nr Woodruff, Ut	Insufficient Data
10023000	Big Creek Near Randolph, Ut	
10024000	Randolph Cr Nr Randolph, Ut	Insufficient Data
10025000	Otter Cr Nr Randolph, Ut	Insufficient Data
10104600	South Fork Little Bear River Near Avon, Utah	Insufficient Data
10104700	Little Bear R Bl Davenport C Nr Avon Ut	
10104900	East Fk Lt Bear Riv Ab Resv Nr Avon Utah	2 Low Outliers
10105000	East Fork Little Bear R Nr Avon Utah	
10106000	Little Bear River Near Paradise, Utah	Diversion/Regulation
10107500	Little Bear River Near Hyrum, Utah	Insufficient Data
10108401	Logan, Hyde Park and Smithfield Canal at Head Near Logan, Ut	Combined discharge In 10109001
10109000	Logan River Above State Dam, Near Logan, Ut	
10109001	Com F Logan R Ab St D And Lo Hp And Sm C N Lo Ut	Low Outlier
10111700	Blacksmith F B Mill C N Hyrum Ut	
10112000	Blacksmith F A H Ran N Hyrum Utah	Insufficient Data
10112500	Blacksmith Fk At Mun. Powerplant, Nr Hyrum, Ut	Insufficient Data
10113500	Blacksmith Fork Ab U.P.&L. Co,S Dam Nr Hyrum, Ut	
10114500	Blacksmith Fk Bl Up&L Plant, Nr Hyrum, Ut	Insufficient Data

Appendix 1, continued.

10115200	Logan River Blw Blacksmith Fork Nr Logan, Utah	Diversion/Regulation
10126400	Box Elder Cr At Mantua Utah	Insufficient Data
10128000	Smith And Morehouse Creek Near Oakley, Utah	
10128200	South Fork Weber River Near Oakley, Utah	
10128500	Weber River Near Oakley, Ut	
10129300	Weber River Near Peoa, Utah	Diversion/Regulation
10129350	Crandall Creek Near Peoa, Utah	Insufficient Data
10129500	Weber River Near Wanship, Ut	Diversion/Regulation
10130000	Silver Creek Near Wanship, Ut	Low Outlier
10130500	Weber River Near Coalville, Ut	Diversion/Regulation
10130700	East Fork Chalk Creek Near Coalville, Utah	Diversion/Regulation
10131000	Chalk Creek At Coalville, Ut	
10132000	Weber River At Echo, Ut	Diversion/Regulation
10132500	Lost Creek Near Croyden, Utah	
10133000	Lost Creek At Devils Slide, Utah	Diversion/Regulation
10133500	Weber River At Devils Slide, Utah	Diversion/Regulation
10133540	Kimball Crk Abv East Canyon Crk Nr Park City, Ut	Insufficient Data
10133600	Mcleod Creek Near Park City, Ut	Insufficient Data
10133700	Three mile Creek Near Park City, Utah	Non-Continuous Record
10133895	East Cyn Cr Ab Big Bear Hollow, Nr Park City, Ut	Insufficient Data
10133900	East Canyon Creek Near Park City, Utah	Insufficient Data
10134500	East Canyon Creek Near Morgan, Ut	Diversion/Regulation
10135000	Hardscrabble Creek Near Porterville, Utah	3 Low Outliers
10135500	East Canyon Creek Bl Diversions Nr Morgan, Utah	Insufficient Data
10136000	Weber River Near Morgan, Utah	Insufficient Data
10136500	Weber River At Gateway, Ut	Diversion/Regulation
10137000	Weber River At Ogden, Utah	Insufficient Data
10137500	South Fork Ogden River Near Huntsville, Utah	3 Low Outliers
10137680	North Fork Ogden River Near Eden, Utah	
10137780	Middle Fk Ogden River Ab Div Nr Huntsville, Utah	Low Outlier
10137800	Middle Fork Ogden River At Huntsville, Utah	Insufficient Data
10137900	Spring Creek At Huntsville, Utah	Insufficient Data
10139300	Wheeler Creek Near Huntsville, Utah	
10139500	Ogden River Near Ogden, Utah	Diversion/Regulation
10140000	Ogden River Below Pineview Dam Near Ogden, Utah	Diversion/Regulation
10140100	Ogden River Bl Pineview Res Near Huntsville, Ut	Diversion/Regulation
10141500	Holmes Creek Near Kaysville, Utah	Historic Flood
10142000	Farmington Cr Abv Div Nr Farmington, Utah	
10142500	Ricks C Ab Diversions, Nr Centerville, Utah	High Outlier, Estimated Flow
10143000	Parrish C Ab Diversions Nr Centerville, Utah	Historic Flood
10143500	Centerville Creek Abv. Div Near Centerville, Ut	High Outlier, Historic Flood
10144000	Stone Creek Above Diversion Near Bountiful, Ut	High Outlier, Estimated Flow
10145000	Mill C At Mueller Park, Nr Bountiful, Utah	Historic Flood
10145125	Storm Drain East Of Orchard Drive At Bountiful, Ut	Urban Site
10145126	Storm Drain To Mill Ck,620 So 200 W,Bountiful, Ut	Urban Site

Appendix 1, continued.

10153500	Provo River Near Kamas, Utah	Diversion/Regulation
10153800	North Fork Provo River Near Kamas, Ut	Low Outlier
10154000	Shingle Creek Near Kamas, Utah	
10154200	Provo River Near Woodland, Ut	Diversion/Regulation
10154500	Weber-Provo Diversion Canal Near Woodland, Ut	Insufficient Data
10155000	Provo River Near Hailstone, Ut	Diversion/Regulation
10155100	Provo River Below Jordanelle Dam, Near Heber, Ut	Insufficient Data
10155300	Provo River Near Midway, Ut.	Insufficient Data
10155400	Spring Creek Near Heber City, Utah	Insufficient Data
10155500	Provo River Near Charleston, Ut	Diversion/Regulation
10156000	Snake Creek Near Charleston, Ut	Diversion/Regulation
10157500	Daniels Creek At Charleston, Utah	Insufficient Data
10158500	Round Valley Creek Near Wallsburg, Utah	Low Outlier
10159500	Provo River Below Deer Creek Dam, Ut	Diversion/Regulation
10160000	Deer Creek Near Wildwood, Utah	Insufficient Data
10160500	Provo River Nr Wildwood, Ut	Diversion/Regulation
10160800	No Fk Provo Riv At Wildwood Utah	
10161000	Provo River At Vivian Park, Utah	Diversion/Regulation
10161500	South Fork Provo R At Vivian Park, Utah	Diversion/Regulation
10162000	Provo R Abv Telluride Power Co. Dam Nr Provo, Ut	Insufficient Data
10162850	Rock Creek Overflow East Of Hiway 189 Nr Provo, Ut	Urban Site
10164500	American Fk Ab Upper Powerplant Nr American Fk, Ut	Outliers, Missing Data
10165500	Dry Creek Near Alpine, Utah	High Outlier
10166000	Fort Creek At Alpine, Utah	Insufficient Data
10167000	Jordan River At Narrows Near Lehi, Utah	Diversion/Regulation
10167220	Bells Canyon Conduit 1000 E. 110000 S.	Urban Site
10167230	Jordan River @ 90Th S Nr Midvale	Insufficient Data
10167242	I-215 Median Drain At Jordan River Nr Murray, Ut	Urban Site
10167300	Jordan River @ 5800 South Nr Salt Lake City, Ut	Insufficient Data
10167500	Little Cottonwood Creek Nr Salt Lake City, Ut	
10168300	Tailrace At Stairs Plant Near Salt Lake City, Ut	Insufficient Data
10168500	Big Cottonwood Cr Nr Salt Lake City Utah	Low Outlier
10169800	Mill Creek Above Elbow Fork Nr Salt Lake City, Ut	Insufficient Data
10170000	Mill Creek Near Salt Lake City, Utah	2 Low Outliers
10170490	Com Flw Jordan River & Surplus Canal @ Slc, Ut	Urban Site
10170500	Surplus Canal @ Salt Lake City, Ut	Diversion/Regulation
10170750	Surplus Canal @ North Temple @ Salt Lake City, Ut	Insufficient Data
10171000	Jordan River @ 1700 South @ Salt Lake City, Ut	Diversion/Regulation
10171305	Parleys Cr Abv Alexander Cr Nr Salt Lake City, Ut	Insufficient Data
10171500	Parleys Creek Near Salt Lake City, Utah	Diversion/Regulation
10171900	Emigration Cr Blw Burr Fork Nr Salt Lake City, Ut	Insufficient Data
10172000	Emigration Creek Near Salt Lake City, Utah	2 Low Outliers
10172200	Red Butte Creek At Fort Douglas, Near Slc, Ut	
10172500	City Creek Near Salt Lake City, Utah	Low Outlier, High Outlier
10172550	Jordan River @ 5Th North @ Salt Lake City, Ut	Diversion/Regulation
10172552	Ninth West Conduit At 536 North, At Slc	Urban Site

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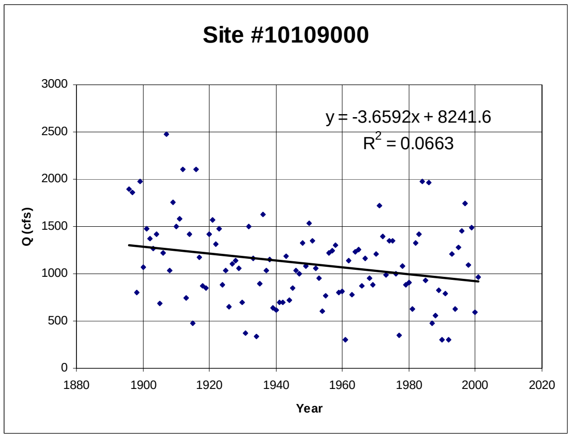
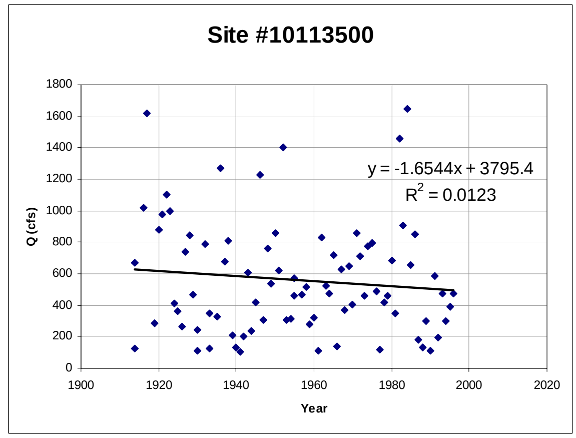
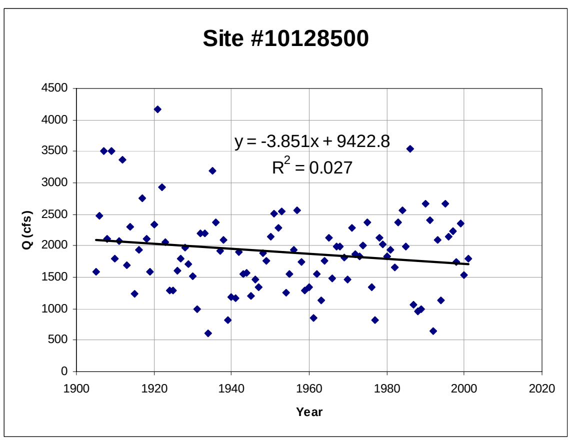
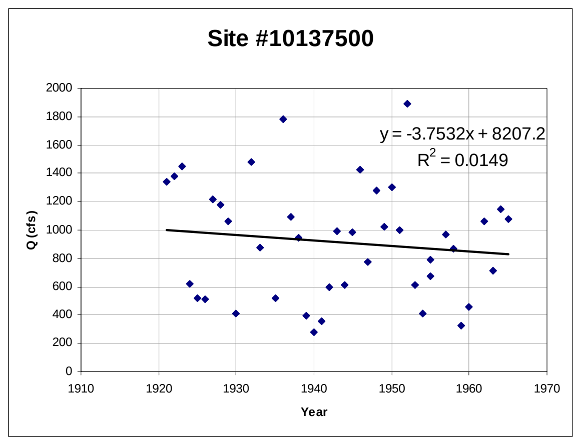
Appendix 2

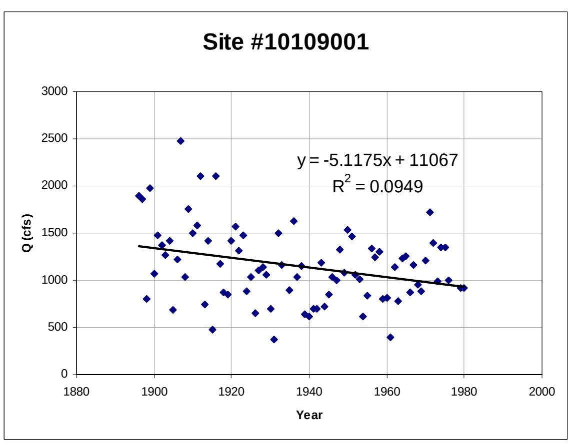
The following charts show the time series of the annual instantaneous peak streamflow with fitted linear regression lines. Plots are made for sites in the study area with at least 30 years of record (see Section 2.6).

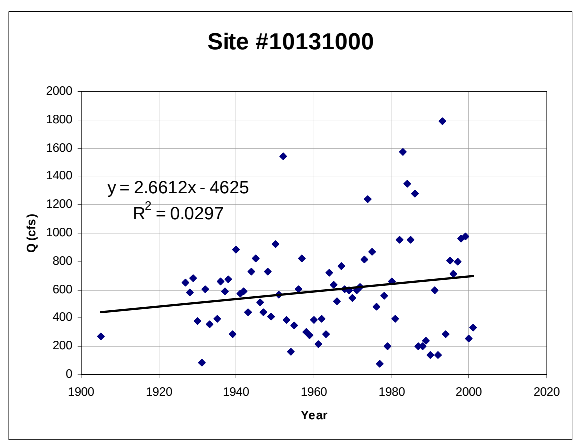


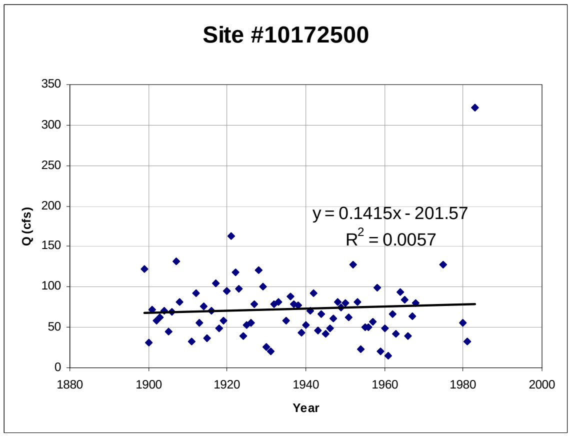


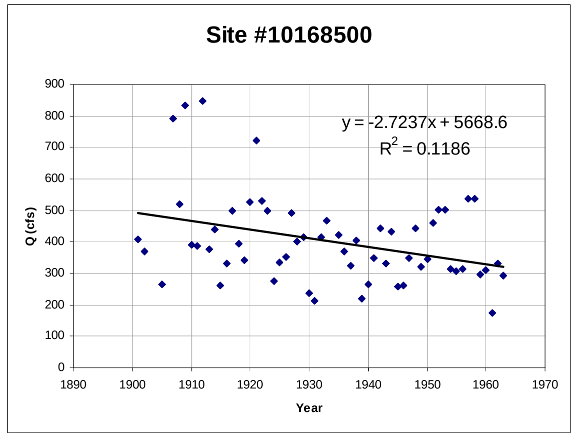


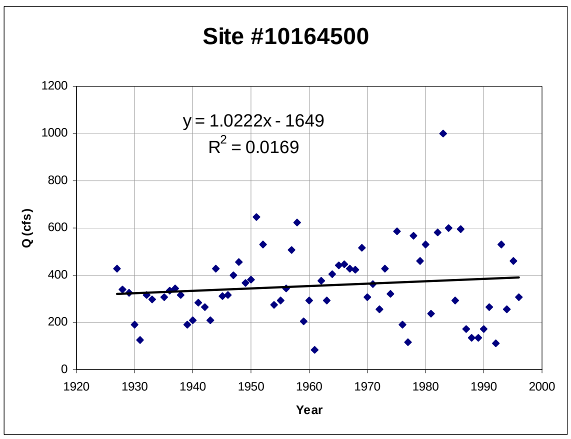


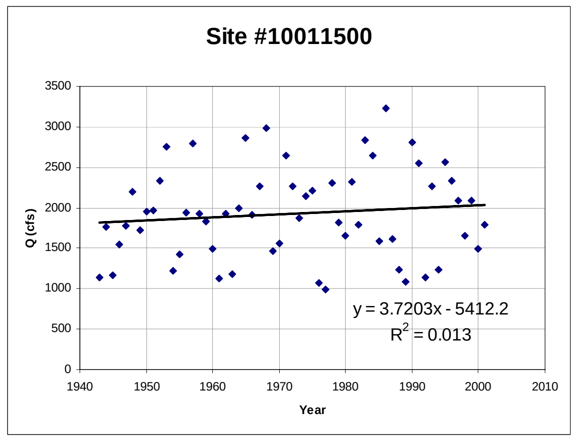


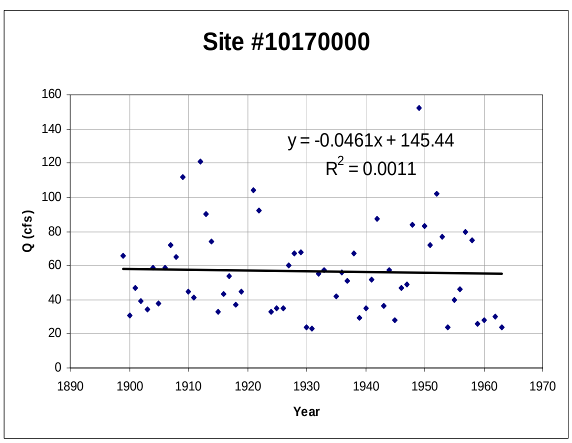


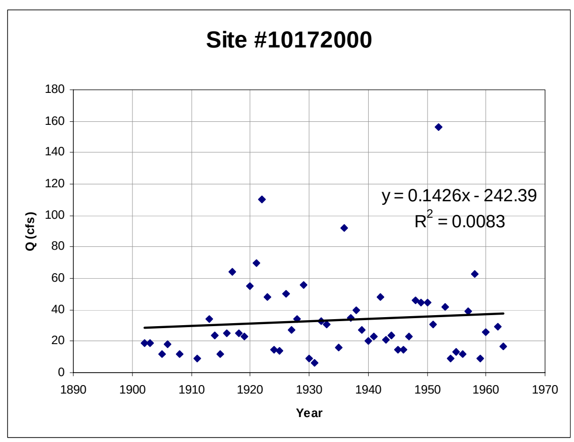

Site #10172500
y = 0.1415x - 201.57
R2 = 0.0057
Q (cfs)
Year

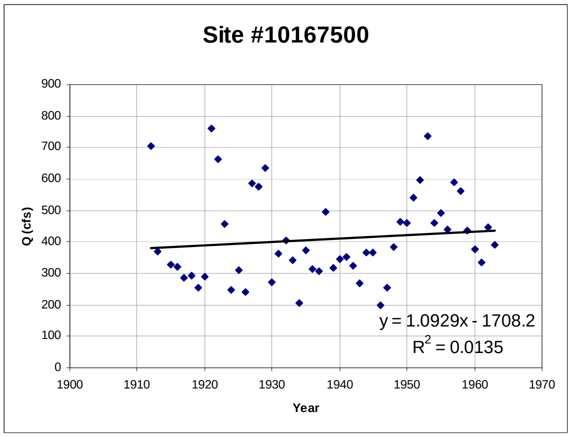

Site #10168500
y = -2.7237x + 5668.6
R2 = 0.1186
Q (cfs)
Year

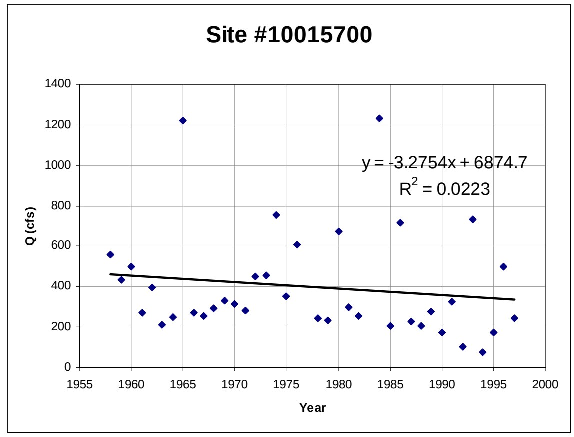

Site #10164500
y = 1.0222x - 1649
R2 = 0.0169
Q (cfs)
Year

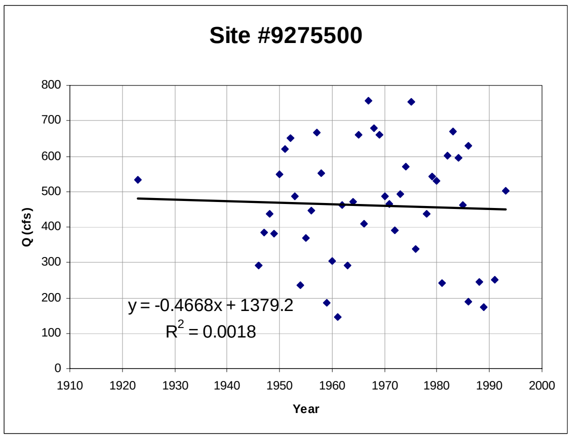

Site #10011500
y = 3.7203x - 5412.2
R2 = 0.013
Q (cfs)
Year

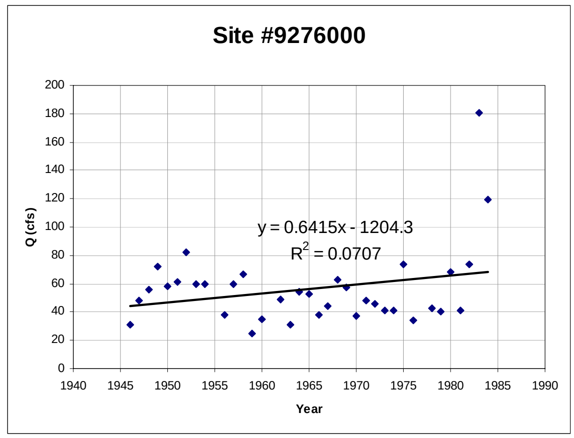

Site #10170000
y = -0.0461x + 145.44
R2 = 0.0011
Q (cfs)
Year

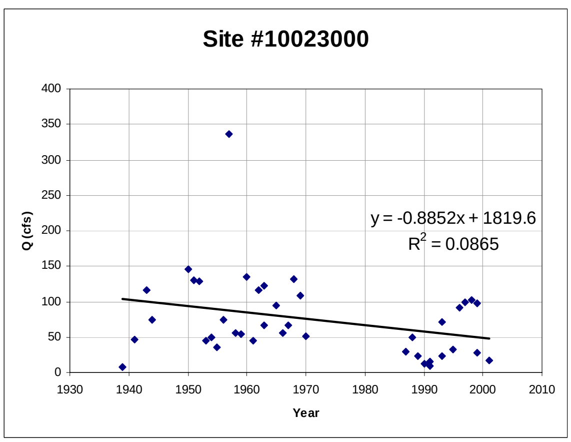

Site #10172000
y = 0.1426x - 242.39
R2 = 0.0083
Q (cfs)
Year

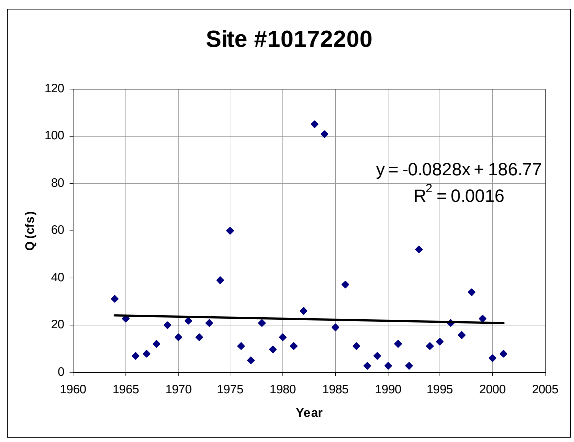

Site #10167500
Q (cfs)
Year
y = 1.0929x - 1708.2
R2 = 0.0135

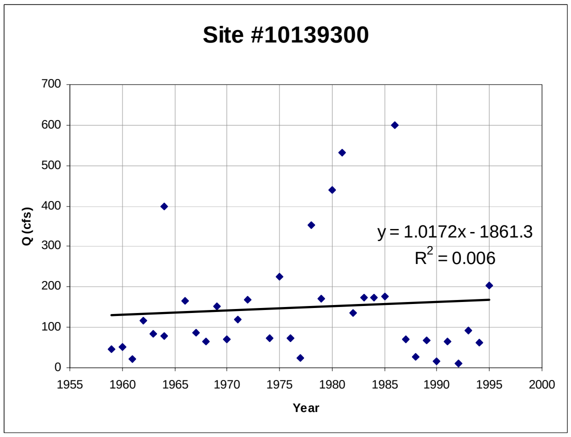

Site #10015700
Q (cfs)
Year
y = -3.2754x + 6874.7
R2 = 0.0223

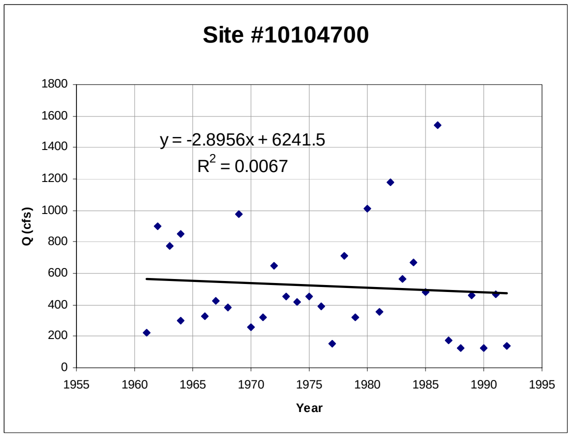

Site #9275500
Q (cfs)
Year
y = -0.4668x + 1379.2
R2 = 0.0018

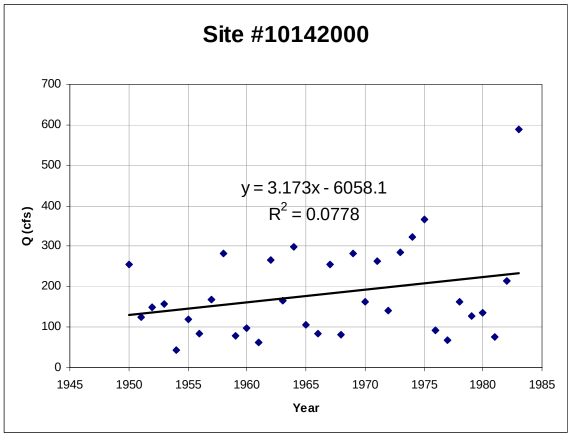

Site #9276000
Q (cfs)
Year
y = 0.6415x - 1204.3
R2 = 0.0707

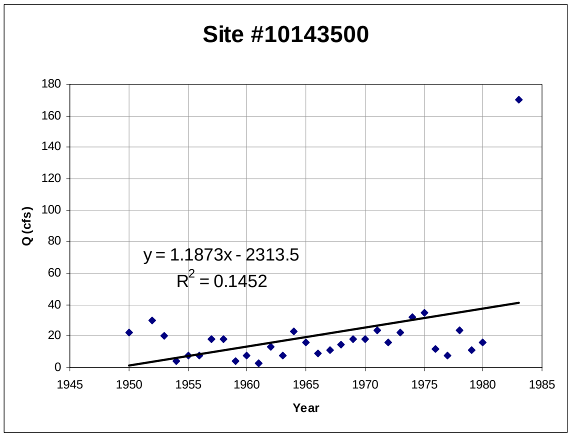

Site #10023000
Q (cfs)
Year
y = -0.8852x + 1819.6
R2 = 0.0865

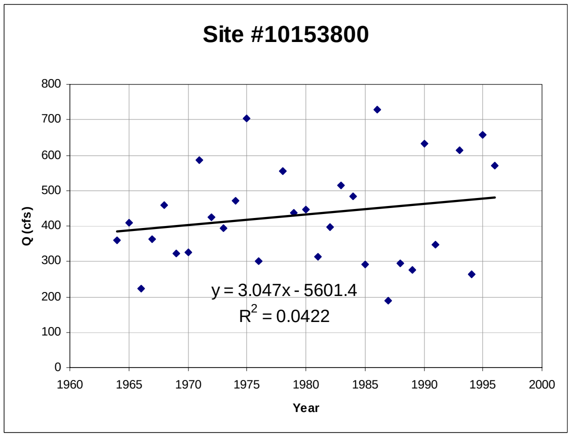

Site #10172200
Q (cfs)
Year
y = -0.0828x + 186.77
R2 = 0.0016


Site #10139300
y = 1.0172x - 1861.3
R2 = 0.006
Q (cfs)
Year


Site #10104700
y = -2.8956x + 6241.5
R2 = 0.0067
Q (cfs)
Year


Site #10142000
y = 3.173x - 6058.1
R2 = 0.0778
Q (cfs)
Year


Site #10143500
y = 1.1873x - 2313.5
R2 = 0.1452
Q (cfs)
Year


Site #10153800
y = 3.047x - 5601.4
R2 = 0.0422
Q (cfs)
Year